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THESIS

DETERMINING THE COST EFFECTIVENESS OF NANO-SATELLITES

by

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September 2014

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13. ABSTRACT (maximum 200 words)

Nano-satellites have grown in popularity and capability since the 1990s. Over ninety were launched into low earth orbit between November 2013 and January 2014. Various Department of Defense services and agencies, including the Department of the Navy, have funded a number of demonstration missions that are being evaluated for military utility. While nano-satellites cost significantly less than traditional space missions, they also provide less capability. A quantitative method is required to determine the cost-effectiveness of nano-satellite missions to inform naval decision-makers.

This thesis develops a framework to compare the cost-effectiveness of nano-satellites. After examining different methods of quantifying small-satellite performance and cost, a generic cost-effectiveness model is developed. The model is demonstrated using two hypothetical scenarios where both nano-satellite and traditional satellite options are considered.

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

AFCAA	Air Force Cost Analysis Agency
COTS	Commercial-Off-The-Shelf
DOD	Department of Defense
EDSN	Edison Demonstration of Smallsat Networks
FBC	Faster, Better, Cheaper
GEOSAT	Geodetic/geophysical Satellite
GFO-2	GEOSAT Follow-On 2
GPS	Global Positioning System
GNC	Guidance, Navigation and Control
ICESat	Ice, Cloud and Land Elevation Satellite
ISR	Intelligence, Surveillance and Reconnaissance
JCIDS	Joint Capabilities Integration Development System
OMB	Office of Management and Budget
ONE	Operational Nanosatellite Effect
PPOD	Poly Picosatellite Orbital Deployer
SATCOM	Satellite Communications
SMCE	Science Mission Cost Effectiveness
SMDC	Space and Missile Defense Command
SPAWAR	Space and Naval Warfare Systems Command
STK	Systems Tool Kit
UHF	Ultra High Frequency

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EXECUTIVE SUMMARY

The continued miniaturization of COTS devices has enabled a surge in the number of nano-satellites designed and launched into space. As consumer electronics continue to pack more capability into consumer devices, the capability of nano-satellites will continue to grow. The commercialization of nano-satellites by companies like Planet Labs will lead to significantly reduced production costs, which will lead to even larger numbers of satellites being launched. The Department of the Navy will need to adapt to this new technology.

The operational community should consider the implications of using nano-satellites as a platform for low cost payloads in space. The Chief of Naval Operations stated the Navy should "consider shifting our focus from platforms that rely solely on stealth…" (Greenert 2012). Nano-satellites could be launched in large numbers at relatively low cost, providing strength in numbers instead of relying on stealth. The Naval forces should consider how they would command and control a large number of satellites. They should also consider how they would operate if adversaries had large numbers of satellites.

The Department of the Navy will face a number of challenging budget decisions in the coming years. Traditional space systems have provided significant capability to the Navy, but at a significant cost. Nano-satellites may be able to provide a subset of the capability at a lower cost, providing an intermediate option instead of a binary fund-or-cancel decision. Decision makers should use the model developed in this thesis to quantify the cost-effectiveness of nano-satellites as they make major decisions.

Traditional satellites are costly and take too long to be useful to warfighters. Many large satellites cost hundreds of millions of dollars, sometimes more than a billion, to build and launch. Large satellite programs often take more than ten years to design, build and launch. Future budget pressures will result in fewer space systems, or a major change in development and/or makeup of

space systems. One solution to the above problems may be the use of low-cost, rapidly produced nano-satellites, which are generally less than a foot long and weigh less than 25 pounds.

Nano-satellites are gaining popularity in large part due to the popularity of the CubeSat standard and the availability of low cost, high performance components. Over ninety were launched into low earth orbit between November 2013 and January 2014. Various Department of Defense organizations are developing nano-satellites to meet their needs (National Reconnaissance Office 2013; Space and Naval Warfare Systems Command 2013). Methods to more accurately determine the performance and cost of nano-satellites are required, which will lead to a more insightful assessment of their value.

Nano-satellites have a number of advantages and disadvantages when compared to traditional space systems. Significant investment in nano-satellite technology development from academic, government and commercial users is quickly increasing the advantages and minimizing the disadvantages of nano-satellites. An examination of high level factors such as requirements flexibility, power generation, and communications throughput can be used to quickly determine if nano-satellites could potentially perform a given mission. If a mission meets many of the advantages and has few of the disadvantages, a nano-satellite solution may be viable and worthy of a detailed investigation.

Cost-effectiveness analysis is a proven method to evaluate the benefit of various alternatives. This thesis applies it to decisions between nano-satellites and traditional space systems. The method described is applied to two vastly different missions: Intelligence, Surveillance and Reconnaissance (ISR) and Environmental Monitoring. The cost model used by Space and Naval Warfare Systems Command to develop nanosat mission costs is described. A generic objectives hierarchy and measures of effectiveness are established which could later be refined for specific missions. Finally, a swing weights matrix is used to rank the importance and variation of performance measures. The cost-effectiveness analysis method outlined in this thesis can be used as a template

for future analysis of nano-satellite systems for any type of mission. With input from appropriate stakeholders and system experts, cost-effectiveness analysis can provide a quantitative method for high impact decision making.

A scenario representative of Intelligence, Surveillance and Reconnaissance (ISR) missions compared Planet Labs' three meter imagers against the WorldView-2 satellite. Planet Labs' twenty-eight Flock-1 satellites achieved an effectiveness of 34% at a cost of $267,150,000. DigitalGlobe's WorldView-2 satellite achieved an effectiveness of 36% at a cost of $496,600,000. A more accurate WorldView-2 satellite model would likely show a significant increase in effectiveness. The combination of Flock-1 and WorldView-2 achieved an effectiveness of 64% at a total cost of $763,750,000.

An example Environmental Monitoring scenario evaluated the cost effectiveness of the planned GEOSAT Follow On-2 (GFO-2) with a notional nano-satellite altimeter system comprised of four satellites. GFO-2 achieved an effectiveness of 73% for a cost of $265,689,164. The four satellite Nano-satellite Altimeter mission achieved an effectiveness of 26% for a cost of $109,159,000.

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I. OVERVIEW

A. PROBLEM STATEMENT

Space systems provide the Department of Defense (DOD) unique access to otherwise unavailable areas for missions such as communications, weather prediction, missile warning, intelligence, surveillance and reconnaissance. Despite this advantage, space systems have a number of problems that limit their use.

Space systems are very costly to develop and operate. Most DOD space programs cost in the billions of dollars and produce only a handful of satellites. Even supposedly low cost “tactical satellites” have cost more than $100 million for missions of only a few years. Another problem is that traditional space systems take a very long time to develop using today’s processes. Acquisition regulations, a limited number of suppliers, and other factors lead to programs that take nearly a decade or more to launch new satellites. Once launched into orbit, many of today’s space systems take months, and sometimes more than a year, to become fully operational. Complex payloads must be carefully tested and calibrated by numerous engineers before warfighters can make use of the system (United States Air Force 2013).

Space is “increasingly congested, contested, and competitive” (Defense 2011). Several competitors and possible adversaries are building space capabilities to match our own. Space is no longer a safe haven for our spacecraft. Current space systems do not account for this fact; they operate more like a public utility than a critical weapon system.

Nano-satellites are a potential solution to these problems. They can be developed in months at very low cost. They can be produced in large quantities, providing resiliency against threats. A major drawback is that nano-satellites provide less capability than traditional space systems. Before the United States

commits to a significant long term investment in nano-satellites, their cost-effectiveness must be considered.

B. NANO-SATELLITE BACKGROUND

1. Small Satellites

Satellites began as relatively small machines. Sputnik-1, the first satellite placed in earth orbit, was approximately 86 kilograms (National Aeronautics and Space Administration 2013). As experience building satellites and launch vehicle capabilities grew, so did satellite volume and mass (Janson 2011). Satellites eventually grew to as much as 18,000 kilograms for Low Earth Orbit and 8,000 kilograms in geosynchronous orbit (Union of Concerned Scientists 2013).

Classes of satellites have not been officially standardized; however, many in the aerospace community describe small satellites in a number of categories. Mini-satellites are less than 1,000 kilograms. Micro-sats are less than 100 kilograms. Nano-satellites are less than 10 kilograms. Pico-satellites are less than one kilogram (Sandau 2006). Anything over 1,000 kilograms is a large or traditional satellite.

A number of factors led to a significant increase in the number of small satellite missions from the early 1990s until today. Efforts to miniaturize electronic and electro-mechanical components enabled significant computing and sensing power in increasingly small packages. Solar cell improvements led to greatly increased efficiency, allowing smaller arrays to be used. The Global Positioning System (GPS) provided time synchronization and position information in very small packages. Networking technology enabled low cost ground stations and facilitated data sharing (Janson 2011). The results of these factors are shown in Figure 1, which depicts the number of satellites under 50 kilograms launched from 2009 to 2013, and SpaceWorks' projections for 2014 to 2020. The "full market potential" shows all announced launches. The SpaceWorks projection is their estimate of the number of launches what will occur.

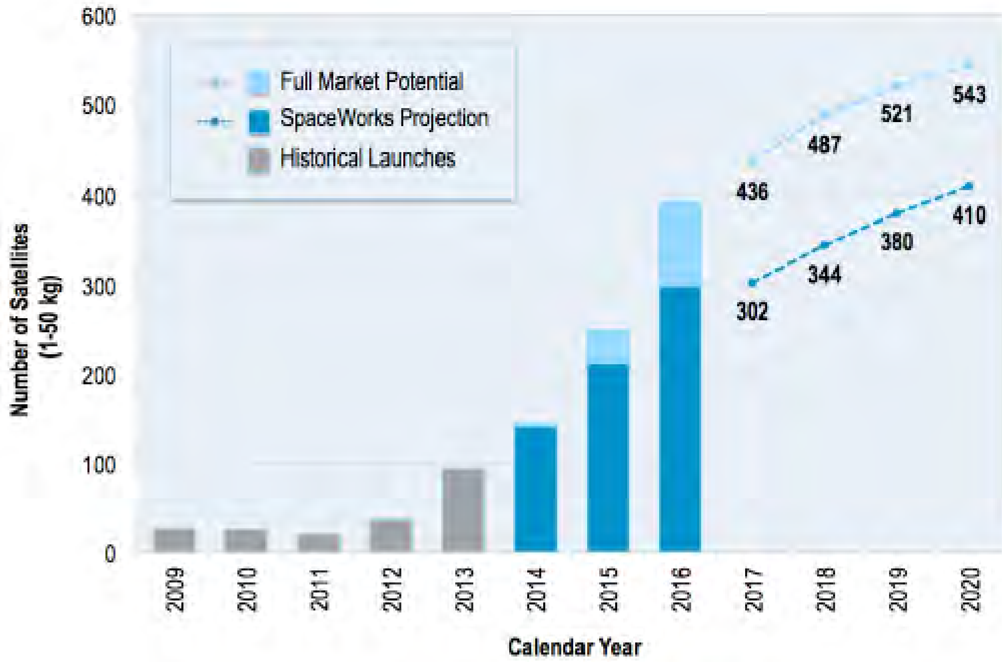

Figure 1. SpaceWorks' Nano/Microsatellite Launch History and Projection (from Buchen 2014)

2. CubeSats

CubeSat is a satellite standard developed by California Polytechnic State University and Stanford University. Originally, a CubeSat was defined as a 10 centimeter cube of up to 1 kilogram mass. This size later became known as a one unit, or "1U." Now various sizes are allowed. 3U has been used for many space missions, and 6U and larger are gaining popularity.

The standard size of CubeSats led to standard components. Many electrical components are built onto 88 millimeter PCB cards, leaving just enough room to fit inside the 100 millimeter envelope of a CubeSat. Most CubeSat designs layer those components into a "stack of cards" configuration. The availability of standard components speeds up development time compared to traditional space systems, which typically use custom components built by hand.

CubeSats are launched into space as secondary payloads, or "rideshares," on large launch vehicles. After delivery of the primary payload to its

intended orbit, the CubeSats are deployed using a spring loaded Poly Picosatellite Orbital Deployer (PPOD) or similar device.

More than 100 CubeSats have been launched to date. On November 19, 2013, a Minotaur 1 launched 28 CubeSats on the Operationally Responsive Space (ORS) Office's ORS-3 mission (Orbital Sciences Corporation 2014). Two days later a Dnepr rocket launched 32 satellites, including 19 CubeSats (Microcom Systems 2014). An Antares rocket put 33 CubeSats in orbit on January 9, 2014 (Orbital Sciences Corporation 2014).

Nano-satellites have demonstrated military utility during a number of recent experiments. The Army's Space and Missile Defense Command (SMDC) Operational Nanosatellite Effect (ONE) demonstrated Ultra High Frequency (UHF) Satellite Communications (SATCOM) capability with ground units (Weeks, Marley and London 2009). The number of military nano-satellites built has continued to rise. The ORS-3 mission included 17 technology demonstration CubeSat missions for the Department of Defense (Klofas, Upcoming CubeSat Launches: The Flood Has Arrived 2013).

While useful for a number of missions, nano-satellites cannot be a replacement for all large satellites. Limitations of technology and physics preclude many missions. For instance, the optics must be much larger than 3U CubeSats to obtain high-quality intelligence imagery from low earth orbit. For example, the primary mirror on the commercial imagery satellites WorldView-2 and GeoEye-2 are both 1.1 meters in diameter(Franklin 2012) and cannot fit into a 0.3 meter 3U CubeSat. Another major limitation for nano-satellites is power generation and storage.

C. RESEARCH QUESTIONS

The promise of low cost nano-satellites is enticing, but how can one be sure that lower cost is actually better? Large satellites are generally considered to be more cost effective (Koelle 1983), but take significantly longer to build. Koelle showed that larger communications satellites provided a lower cost per

channel than smaller satellites. Nano-satellites are much less capable, but can be designed, produced and employed in a very short time. How can one determine when a nano-satellite provides better value than traditional large satellites? Can one build a model to reliably show when nano-satellites are a better value?

The Department of Defense and other government agencies have rapidly adopted nano-satellites for technology pathfinders and even some operational mission demonstrations (Klofas, Upcoming CubeSat Launches: The Flood Has Arrived 2013). The National Reconnaissance Office established a CubeSat program in 2007 (National Reconnaissance Office 2013). The Navy's Program Executive Office Space Systems is developing plans for a program of record based on nano-satellites (Space and Naval Warfare Systems Command 2013). A quantifiable method to compare the cost effectiveness of nano-satellites to larger satellites is required for informed decision making.

D. LITERATURE REVIEW

Little information is available specifically about the value or utility nano-satellites. However, a significant amount of information was collected and analyzed about NASA's Faster, Better, Cheaper (FBC) series of small satellites. Also, much has been debated about the Operationally Responsive Space (ORS) Office's small satellite missions. The sections below describe previous research on cost models and performance measurement for various small satellite efforts, which helped guide the effort to develop cost-effectiveness model for nano-satellites.

1. Small Satellite Cost Models

In the early 1990s, it became apparent that a single cost estimating method was not appropriate given the wide range of satellites being developed. The techniques used over the previous 30 years to develop large, well-funded space programs did not work well for smaller satellites with significantly smaller budgets. To help remedy the problem, Aerospace Corporation developed the

Small Satellite Cost Model. A key step in the model development was to understand the difference between large and small spacecraft. The procurement processes, rather than the size or mass of the spacecraft, were found to be a major cost and schedule driver for large programs. (Abramson and Bearden 1993)

Efforts continued to reduce the cost of small satellites. Practices that helped reduce cost for small programs were identified. Acquisition regulations for documentation and reviews were found to be a key cost driver, and were reduced for smaller programs (D. A. Bearden, Small-Satellite Costs 2001). Downsizing from large traditional satellites meant smaller facilities could be used, reducing costs and a significant barrier to competition. Small programs often combined the traditional engineering design unit and flight hardware unit into a single “protoflight” unit that served as both prototype and final product (D. A. Bearden, Small-Satellite Costs 2001). Redundancy was avoided in favor of simpler designs. Fixed price contracts were often used.

RAND Corporation’s *Guidelines and Metrics for Assessing Space System Cost Estimates* provides a chapter summarizing techniques and items to consider for small satellites. One key point is that satellite price and value are not equivalent. While smaller satellites generally have a much lower cost, it does not mean they have a much lower value. The proliferation of small satellites also provides opportunities for a wide range of component suppliers, significantly increasing competition as compared to large satellites. (Fox, Brancato and Alkire 2008)

2. Faster, Better, Cheaper Satellites

NASA’s series of Faster, Better, Cheaper (FBC) missions was analyzed by multiple authors to see if they were in fact faster, better and cheaper than larger traditional systems. FBC missions were faster and cheaper than traditional missions, but a metric for “better” is subjective. FBC missions were less reliable than traditional ones (Mosher et al. 1999). Despite a lower failure rate for

traditional missions, the dollar value of systems lost was significantly higher. A higher flight rate for FBC led to a greater quantity and variety of missions (Mosher et al. 1999).

A concept called Science Mission Cost Effectiveness (SMCE) was proposed to compare value. To calculate the SMCE, one must first calculate the number of instrument-months by summing the number of months each instrument on the system was in operation. The SMCE ratio is then calculated by dividing the sum of instrument-months by the total cost of the mission. The results were aggregated to compare large and small systems using a "mission class" SMCE by dividing the sum of instrument-months of all missions in the class by the sum of total costs for all missions in the class. Analysis showed FBC missions were 57% more cost effective than traditional systems (Mosher et al. 1999).

3. Operationally Responsive Space

A comparison of traditional strategic Intelligence, Surveillance and Reconnaissance (ISR) satellites, low-cost satellites launched in response to an emerging conflict, and a hybrid approach was conducted by Fram (2007) to examine the utility of various options for Operationally Responsive Space missions. The quality of a pass, the timing of the pass, and the sensor quality were defined on a scale of zero to one. All three were multiplied together to find the utility score for a single pass. The cost-effectiveness of each architecture was calculated as the sum of all pass utility scores divided by the total cost. For a number of scenarios, the responsive architecture had lower utility scores but the best ratio of utility to cost. (Fram 2007)

4. Complexity

The role of complexity in driving cost, schedule and mission failure was evaluated by several authors. Bearden (2003) calculated a normalized "complexity index" from system technical parameters, programmatic factors, and redundancy policies. Plots of development time versus complexity and cost

versus complexity showed that systems above 70% complexity were very likely to fail or be impaired. While the complexity index cannot predict failure, it can show when a mission has similar cost or schedule constraints to missions that have failed (D. A. Bearden 2003).

Further evaluation of the complexity index concept led to the development of the Complexity Based Risk Assessment tool by Aerospace Corporation. Since subsystem cost and schedule data is difficult to get, the tool works only at the system level. There is still room for improvement as the correlation of variables has not been fully explored, and some variables may be inter-related. For example, the need for high power generation and the use of articulating solar panels is likely related. (Bearden, Cowdin and Yoshida 2012)

E. CHAPTER SUMMARY

Nano-satellites are gaining popularity in large part due to the popularity of the CubeSat standard and the availability of low cost, high performance components. Various Department of Defense organizations are developing nano-satellites to meet their needs (National Reconnaissance Office 2013) (Space and Naval Warfare Systems Command 2013). While nano-satellites can be built quicker and at much lower cost, many question their value. Methods to more accurately determine the performance and cost of nano-satellites are required, which will lead to a more insightful assessment of their value.

II. ENABLING FACTORS FOR NANO-SATELLITE MISSIONS

Before expending the effort to define the cost effectiveness of a potential nano-satellite system for a specific mission, some high level considerations should be evaluated. Nano-satellites have a number of disadvantages that limit their use for some missions, but have many advantages that enable otherwise infeasible missions. If the mission fits most of these factors, it can likely be accomplished with nano-satellites and they should be evaluated in more detail. If the mission does not fit the majority of these factors, it is likely not worth the effort to evaluate the cost-effectiveness of nano-satellites in more detail.

A. DISADVANTAGES

Nano-satellites have a number of disadvantages when compared to traditional satellites. Areas to consider include requirements flexibility, mission orbit, coverage, data downlink and power duty-cycle. If many of these factors are required for a particular mission, it may not be feasible for current nano-satellites. Many of these disadvantages are being addressed by current technology development efforts in the nano-satellite community and may not be limiting factors in the future.

1. Rigid Requirements

Those conducting the evaluation must have a thorough understanding of the system requirements to allow for trades. There are many cases where nano-satellites can only meet some of the system requirements, but at a very attractive price. The requirements must be flexible enough to consider these options. If any system that does not meet 100% of requirements is thrown out, then nano-satellites will almost always be eliminated from consideration.

2. High or Precise Orbits

Nano-satellites have been primarily launched to low earth orbit. While designs for other orbits and even inter-planetary missions are in development

(Interplanetary Small Satellite Conference 2014), they have yet to be proven. If a mission requires the satellites to go beyond low earth orbit, nano-satellites are likely not the best choice for a low risk mission in the near future. The fact that a previous system was beyond low earth orbit should not automatically preclude the use of nano-satellites to replace or augment that mission. Consider that previous analyses that determined one or more satellites at a higher orbit was the most effective design may have been completed before the recent developments in nano-satellite technology.

Missions that require very precise orbits may be difficult for nano-satellites to achieve if there are no ride-share opportunities to get to that orbit. The low cost of nano-satellites is contingent on low cost launch opportunities. There are ongoing small launch vehicle efforts that may eliminate this factor in the future (National Aeronautics and Space Administration 2013).

3. Constellation Maintenance

Nano-satellites lack propellant for station keeping maneuvers to maintain a steady constellation. The use of propulsion was prohibited until revision 13 of the CubeSat standard was released in 2014 (California Polytechnic State University 2014). If launched into an orbital plane, the satellites would slowly drift closer and/or further apart depending on various factors. If the mission cannot accept any gaps in coverage, nano-satellites are likely not the best solution. This precludes the use of nano-satellites for most instantaneous communications missions, but may allow their use for store-and-forward type missions.

Several different nano-satellite missions aim to close this capability gap in the near future. Designs for cold gas thrusters, Hall effect thrusters, and solid state propellant are in development and some prototype systems are being tested (Cheney 2014).

4. Data Downlink

Nano-satellites are generally very power limited due to the very small solar arrays available. The transmitter is one of, if not the highest power consuming devices on board. Many previous nano-satellite missions have been limited to transmission rates of only kilobits per second using UHF links. Some missions have used S-band links to get approximately one megabit per second downlinks (Klofas and Leveque, A Survey Of CubeSat Communication Systems: 2009-2012 2013). Hence, getting information off the satellite is one of the limiting factors for a nano-satellite mission. If a mission requires the transmission of significant amounts of data, nano-satellites may not be a good fit.

Ongoing efforts exist to further reduce this limitation for nano-satellites. Planned missions will test increasingly higher bandwidth radios. Other technologies such as modulated retro-reflectors can enable one-way high speed transfer at a very low power cost to the nano-satellite (Wayne, Lovern and Obukhov 2014).

5. Duty Cycle

Due to the power limitations described previously, nano-satellites must either operate using very low power, or choose to operate only over key locations on the ground. High power operations cannot be maintained throughout the entire orbit. This may preclude nano-satellites from missions that require continual high power operations. The use of many nano-satellites working cooperatively may achieve the mission at the cost of increased system complexity.

B. ADVANTAGES

Nano-satellites have many advantages over traditional satellites. Nano-satellites are much lower cost, can be developed rapidly, can provide the latest data processing technology, and provide strength in numbers. These advantages are likely to grow over time as multiple generations of nano-satellites are built. If

many of these factors align with the needs of a mission, it may be well suited for a nano-satellite solution.

1. Cost

Nano-satellites cost significantly less than traditional satellites. Complete CubeSat development kits can be purchased as little as $7,500 (Pumpkin 2014) for academic focused missions. Traditional satellites often cost hundreds of millions of dollars. For example, the Wideband Global SATCOM (WGS) satellites cost the Air Force approximately $425 million each in FY10 dollars (U.S. Air Force 2013). If cost is one of the primary considerations for a mission, nano-satellites are likely at an advantage.

2. Rapid Development

Development timelines for nano-satellites are usually much shorter than traditional satellites. One of the original goals of the CubeSat was to enable students to design, build and fly satellites within their course of study. Some nano-satellites are developed in very short time frames. Planet Labs claims to design a new generation of 3U CubeSats in approximately eight weeks, and at peak production they complete two satellites per day (Boshuizen et al. 2014). If rapid development is required, nano-satellites have a distinct advantage over traditional satellites.

3. Data Processing

Data throughput from the satellite to the ground is generally a limitation, however, there are options for a nano-satellite mission to get around this restriction. The radiation level in low earth orbit is relatively low and the latest Commercial-Off-The-Shelf (COTS) components for digital processing can be used. This technology could allow additional on-board processing and minimize the amount of data that must be sent to the ground. Current COTS processors used in nano-satellite designs provide nearly forty times the processing capability as traditional satellite components. With the addition of fault tolerant computing

techniques, the COTS processors give nano-satellites an advantage when significant onboard processing is required (Rudolph et al. 2014).

4. Strength in Numbers

For missions that do not require continuous coverage, nano-satellites may be at an advantage over larger systems. A large number of nano-satellites could provide a much higher re-visit rate than a system using only a handful of large satellites. An example is NASA's Edison Demonstration of Smallsat Networks (EDSN) system, which tested inter-satellite communications technology with a swarm of eight 1.5U CubeSats (Hanson et al. 2014). A technology demonstration with eight traditional satellites would be cost prohibitive. Another example is Planet Labs, which aims to achieve once per day revisit of the entire Earth using more than two hundred nano-satellites (Boshuizen et al. 2014). If a large number of satellites are required for a mission, nano-satellites likely have an advantage.

C. CHAPTER SUMMARY

Nano-satellites have a number of advantages and disadvantages when compared to traditional space systems. Significant investment in nano-satellite technology development from academic, government and commercial users is quickly increasing the advantages and minimizing the disadvantages of nano-satellites. The factors discussed in this chapter can be used to quickly determine if nano-satellites could potentially perform a given mission. If a mission meets many of the advantages and few of the disadvantages, a nano-satellite solution may be viable and requires additional investigation.

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III. VALUE SYSTEM

A. BUSINESS CASE ANALYSIS AND COST EFFECTIVENESS

> A business case analysis, sometimes referred to as a cost benefit analysis, is a comparative analysis that presents facts and supporting details among competing alternatives. (Government Accountability Office 2009)

Analysis of alternatives, cost-effectiveness analysis and economic analysis are terms that are often used interchangeably; however, they have distinct meanings. Each is a type of business case analysis (Government Accountability Office 2009). The U.S. Office of Management and Budget (OMB) defines cost-effectiveness as "a systematic quantitative method for comparing the costs of alternative means of achieving the same stream of benefits or a given objective." OMB further states that "cost-effectiveness analysis is appropriate whenever it is unnecessary or impractical to consider the dollar value of the benefits provided by the alternatives under consideration" (Office of Management and Budget 1992). It is often difficult to assign a dollar value to the outcome of military operations; therefore, cost-effectiveness analysis was the most appropriate method to compare nano-satellites with traditional satellites.

B. PREVIOUS COST EFFECTIVENESS EFFORTS

Science Mission Cost Effectiveness was used to compare NASA's Faster Better Cheaper series of satellites against traditional satellites. The effectiveness was measured by calculating "instrument-months" by summing the number of months each instrument on the system was in operation. The cost effectiveness ratio was the number of instrument months divided by the cost (Mosher et al. 1999). While the number of instrument-months was a good metric for the quantity of science measurements provided, it did not account for the quality of measurements.

Larger satellites have generally provided more capability when compared to smaller satellites. The gain for parabolic antennas is calculated as $4\pi A\eta / \lambda^2$ where A is the area of the antenna, eta (η) is the efficiency of the antenna, and lambda (λ) is the wavelength of the signal (Gordon and Morgan 1993). Larger satellites can accommodate larger antennas and therefore usually provide more capability for communications or radio-frequency sensing missions. Another example where larger satellites outperform small satellites is optics. The Rayleigh limit for angular resolution with a circular optic is $1.22\lambda / D$ where lambda (λ) is the wavelength and D is the diameter of the optic (Olsen 2007). As the diameter increases, the angular resolution decreases; therefore, satellites that can accommodate larger optics provide better capability. Since the abilities of larger satellites are generally greater than those of smaller satellites, the instrument-months metric was not appropriate.

Fram analyzed potential Operationally Responsive Space missions using the total number of sensor passes, the quality of the passes, the quality of the sensor, and the timing of the pass (during peace or conflict) to calculate the benefit of large and small satellites (Fram 2007). While a significant improvement over the Science Mission Cost Effectiveness, a drawback remained. The measures of effectiveness were coarsely measured as high, medium or low value. This was likely because the systems analyzed were hypothetical with little detailed design information available.

The high cost of space system acquisition has little room for error. The Department of the Navy requires a more informed process for analyzing the business case for nano-satellites versus traditional satellites. A new cost effectiveness model is developed in this thesis to serve as a template for future analysis of naval space needs.

C. COST MODEL

The Space and Naval Warfare Systems Command (SPAWAR) developed a rough order of magnitude cost model for proposed nano-satellite efforts by

PEO Space Systems. The model was based on an acquisition category III program of record judged to be similar in scope to the proposed effort. The project team identified the number of satellites and payloads to be procured, as well as when launches and operations would occur. The number of ground stations and other supporting ground equipment was determined. A mix of labor types from acquisition management to systems engineering management was established and the number of work hours estimated. All of these factors were combined into the "point estimate," which was the starting point of the cost model.

Realized cost information from the National Reconnaissance Office's Colony I Cubesat program and the Vector Joint Capability Technology Demonstration was used to set expected production learning curve cost reductions. Estimated launch costs were based on a commercial launch provider proposal. The program office labor cost was estimated based on the size of the team supporting Vector.

Additional price factors were added to the point estimate to calculate the total price. Program executive office and systems command overhead costs for managing and supporting programs were added. The price of inflation was calculated from the base-year estimate and resulted in then-year costs.

The overall cost was then "risk-adjusted" to account for uncertainty in the price. Each major component of the cost estimate was assigned a cost distribution according to the Air Force Cost Analysis Agency Cost Risk Analysis Handbook. Costs with less supporting cost information were assigned high risk, and those costs with sufficient supporting information were assigned low risk. A pre-defined triangular distribution was applied to each risk category and a Monte-Carlo simulation was run to find the Risk Adjusted Mean cost.

SPAWAR granted permission to use and modify the cost model for the purposes of this research effort. SPAWAR did not review or validate the modified cost model or results.

D. EFFECTIVENESS MODEL

A model was developed to measure the effectiveness of various satellite systems to meet naval needs. A generic template was created with the intent it would be modified to meet the requirements of a given scenario. First, an objectives hierarchy and measures of effectiveness were established. Threshold and objective values were set for each measure of effectiveness. A notional importance for each measure was decided by the author. For real missions, the mission stakeholders would decide the importance of each measure. The swing weight matrix was established to weight the objectives.

1. Objectives Hierarchy

High level mission objectives are often vague and difficult to translate into measurable terms. An objectives hierarchy is a means to decompose high level objectives into smaller and smaller pieces until they can be quantified. Figure 2 shows a notional objectives hierarchy from the NASA Risk Management Handbook that decomposes safety, technical, cost and schedule objectives. Each high level objective is divided into a number of lower level objectives. If the lower level objectives are not quantifiable, they are divided again and again until they are quantifiable (Dezfuli et al. 2011).

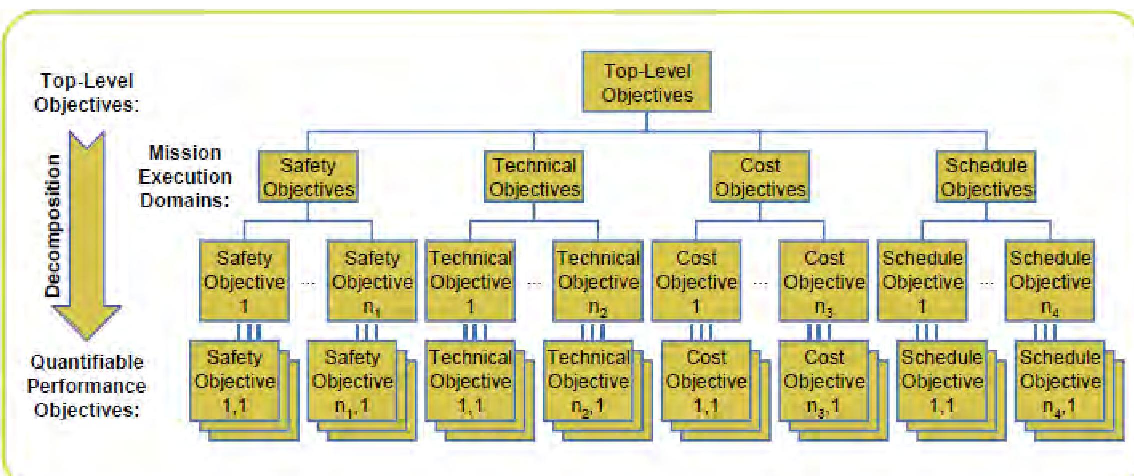

Figure 2. Notional Objectives Hierarchy (from Dezfuli et al. 2011)

Using the NASA Risk Management Handbook as a guide, an objectives hierarchy was created for a generic Naval space mission. The top level mission was broken into objectives for time to operations, payload performance, persistence, responsiveness and resiliency as shown in Figure 3. This generic example can be used as a template in the future, and the second level objectives can be altered or further divided for the specific mission at hand.

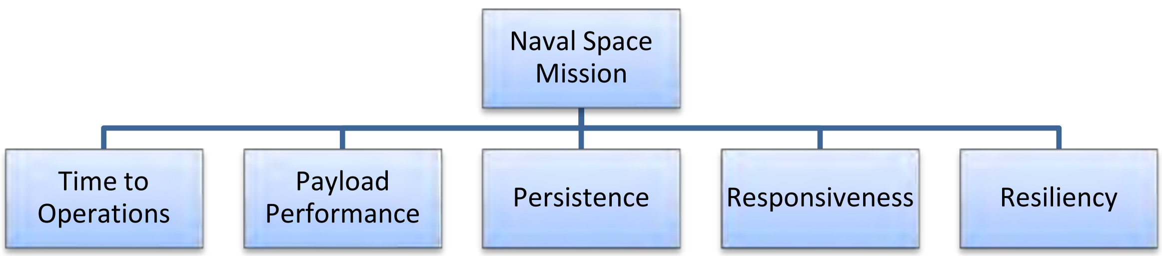

Figure 3. Notional Naval Space Mission Objectives Hierarchy

2. Measures of Effectiveness

The top level mission objectives from the objectives hierarchy were divided into quantifiable sub-objectives. There are a number of ways to measure each objective to determine system effectiveness. Each sub-objective and potential measures for them are described below.

a. Time from need to on-orbit operations

A system that is available to be used is more valuable than one that is not. This metric captures the value of time. The measurement is the number of months from when a need is officially recognized, such as the signing of a Joint Capabilities Integration Development System (JCIDS) requirements document, to when the system is performing the intended mission on orbit. The metric could be further divided into time to develop, time to produce, time to launch, and time to checkout/calibrate, if the level of analysis required it.

b. Payload performance

The payload performance measure will depend heavily on the selected mission; however, a number of metrics have broad application. The quality of the sensor could be defined as the resolution of a camera or the number of bits of dynamic range for acquired signals. The quality of a satellite pass over a target could be defined as the number of degrees off nadir the sensor must be pointed to acquire a target. The number of passes over targets will depend on target locations, the available orbit and the number of satellites in the system. The timing of passes could also be measured to differentiate the value of peacetime or wartime sensor readings.

c. Persistence

Persistence is the ability of a system to provide near continuous coverage of a target area. One measure could be the percent of time a satellite is overhead of a particular target area. Persistence could also be measured by the average revisit rate in minutes.

d. Responsiveness

The responsiveness is the speed at which the system provides results. The access time could be measured as the time from satellite tasking to receipt of the result. It could also be measured as number of sensor readings sent to ground. Both of these measures could help account for sensor and communications link limitations in the system.

e. Resiliency

The National Space Policy says the United States must “address mission assurance requirements and space system resilience in the acquisition of future space capabilities and supporting infrastructure” (President of the United States 2010). There are a number of ways to define resiliency. One measure could be the change in performance of the system if one satellite is lost. The same

measure could be used with ground stations or other critical nodes. Another potential measure of resiliency is the cost to an adversary to defeat the system.

f. Other measures

Other benefits to the use of nano-sats exist but may be more difficult to measure quantitatively. One example is learning experience. Traditional systems often take a decade to develop and last for another decade or more, so the typical acquisition professional only sees two or three systems developed during a career. There is likely value in the additional experience gained by producing and operating a larger number of smaller satellites. The shortened program timeline of smaller satellites will also provide additional experience to the space workforce. Nanosats are often developed, launched and operated in only a few years.

Another potential benefit of nanosats that is difficult to measure is the industrial base effects. Many aerospace firms experience significant swings in business as satellite orders wax and wane. Some aerospace firms cannot survive the downturns and go bankrupt or are purchased by larger firms, reducing the national capacity to build satellites. Even the large firms cut their workforce to match the business demand, leaving many aerospace workers without aerospace related jobs. The quality of the workforce suffers when aerospace workers do not practice their trade continually.

3. Swing Weights

Swing Weights is a technique that accounts for both importance and variation of value measures when performing multi-objective decision analysis. A swing weight matrix was established to define the relative value of the importance and variation of measures of effectiveness. The top represents the importance of the measure, while the side represents the variation. Measures with more variation are given more weight than those with less variation. The swing weight matrix allows for the use of intuitive experience most people have with deciding importance, while simultaneously documenting the rationale used

to decide the weights for potential review by higher authorities. (Parnell and Trainor 2009)

The first step in implementing swing weights is to decide the scale for importance. A simple scale of low, medium and high was used because it was easy to implement and is commonly used throughout the Navy. The definition of high, medium and low was left undefined, but could be formalized in the future. The importance scale was entered on the horizontal axis of the swing weight matrix, as shown in Figure 4. The importance scale could be expanded to have more possible rankings in the future if necessary or desired.

Threshold and objective values for each measure of effectiveness were established. The threshold was defined as the minimum acceptable performance level, below which the system provided no value for the given scenario. The objective was defined as the maximum performance level, beyond which the system provided no extra value for the given scenario. Notional threshold and objective values for each measure of effectiveness were chosen based on the author's judgment and could be changed in the future.

The raw score for each system for each measure of effectiveness was then determined or calculated. Most scores were either calculated by modeling and simulation, or found in literature about the system in question. The raw scores were used to calculate the variation between the systems. Scores were then scaled as a percentage by dividing the raw score by the range between the threshold and objective for the measure of effectiveness.

Next the variation scale was decided. Again, a simple scale of low, medium and high was used. Variation was measured as the difference between the maximum and minimum scaled score for that measure of effectiveness. A simple formula was used to define the scale of variation. Low was any value where the variation between the evaluated systems was less than or equal to 33%. Medium was defined as greater than 33% and less than or equal to 66% of the range. High was greater than 66% variation. The variation scale was entered

on the vertical axis of the swing weight matrix, as shown in Figure 4. As with the importance scale, the variation scale could be expanded in the future.

The weight assigned to each category in the matrix followed a basic set of rules. Any cell of equal importance, but less variation than another cell, must be weighted less than the other cell. Any cell of equal variation, but less importance than another cell, must be weighted less than the other cell (Parnell and Trainor 2009). The high importance, high variation cell was set to a value of 100, and the low importance, low variation cell was set to 1. Notional weights in the other cells were chosen by the author to be consistent with the rules described above. The matrix weights should be developed by an expert team for any future cost-effectiveness analysis.

		Importance of the value measure to the decision		
		Low	Med	High
Range of variation of the value measures	Low	1	25	75
	Med	12	50	90
	High	25	75	100

Figure 4. Raw Swing Weight Matrix

Raw swing weights were taken from the swing weight matrix based on the user defined importance and the calculated variation between the systems. A normalized swing weight was calculated by dividing the raw swing weight of each

measure of effectiveness by the sum of all raw swing weights. This resulted in normalized swing weights between 0 and 1, or on a percentage scale.

Finally, the effectiveness for each measure was calculated by multiplying the scaled score by the normalized swing weight. The total effectiveness of each system was the sum of effectiveness for all measures. The total effectiveness of each system was between 0 and 1, or on a percentage scale.

4. Modeling and Simulation

Systems Tool Kit (STK) is a three-dimensional, physics-based modeling and simulation tool formerly called Satellite Tool Kit. STK allows users to define platforms such as satellites, aircraft and ships and model communications between them. It also simulates the performance of sensor systems on those platforms. The interactions between platforms are simulated in the context of a scenario the user defines. "Figures of Merit" are a means to measure system performance and extract it for further evaluation. STK provides access to an online database of space objects called the STK Data Federate, which uses publicly available orbit data from spacetrack.org to show the location of satellites. (Analytical Graphics, Inc. 2014) Each system was evaluated using a model created in STK.

E. CHAPTER SUMMARY

Cost-effectiveness was determined to be the most appropriate method to evaluate nano-satellites against traditional satellites. The cost model used to develop nanosat mission costs was described. A generic objectives hierarchy and measures of effectiveness were established and could later be refined for specific missions. Finally, the swing weights matrix was used to rank the importance and variation of performance measures.

In the following chapters, two reference scenarios were generated to compare the cost effectiveness of nano-satellites against traditional satellites. The mission areas were based on components of Space Force Enhancement as

defined in Joint Publication 3-14 (Joint Chiefs of Staff 2013). The mission areas were purposefully left broad to assess the value of a range of missions, instead of diving into technical details of one implementation or another. If this methodology is used for acquisition decision making, the evaluator or team can go into significant technical detail if desired.

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IV. INTELLIGENCE, SURVEILLANCE AND RECONNAISSANCE SCENARIO

A. SCENARIO

A conflict erupts along a disputed border. The combatant commander requests additional imagery capability to support operations. A notional conflict area in a mid-latitude region was defined and labeled as the North East. This scenario represents the Intelligence, Surveillance and Reconnaissance (ISR) component of Space Force Enhancement from Joint Publication 3-14.

Figure 5. North East Target Area

Two satellite imagery options were evaluated for performance and cost to determine their cost effectiveness. Traditional space systems were represented by the WorldView-2 satellite. Nanosats were represented by Planet Labs' twenty-eight 3-unit CubeSats with approximately three meter resolution.

The author modified the generic objectives hierarchy from Section III.D.1 to fit the scenario. The high level objectives were broken down into measurable

components. Thresholds and objectives were established, and the swing weight matrix described in section III.D.3 was applied to the scenario. The end result was captured in Microsoft Excel and is shown in Table 1.

Table 1. ISR Scenario Effectivess Model

Measure of Effectiveness	Measure of Performane	Metrics	Threshold	Objective	Importance	Var. %	Var. bin
Payload performance	Resolution	STK FOM > MinGSD > Grid Stats Report > Average	10	0.5	Med	53%	Med
	Panchromatic Dynamic Range	Literature: bits	8	16	Med	38%	Med
	IR Dynamic Range	Literature: bits	8	12	Low	0%	High
Persistence	Percent of target area covered per day	STK CoverageDefinition > PercentCoverage Report	5%	100%	High	39%	Med
	Average Revisit Rate (hours)	STK FOM: AvgRevisitTime > Grid Stats Report > Average	72	8	High	75%	High
	Number of passes (per day)	STK FOM > TotalAccesses > Grid Stats Report > Average	0.25	3	Med	60%	Med
Resiliency	Capability with one lost satellite	1 - Single sat % of constellation	50%	98%	Med	0%	High
	Capability with one lost ground station	1 - Single ground station % of system	50%	98%	Med	0%	High

B. PLANET LABS

> Planet Labs is a privately financed company building small imaging satellites to provide an unprecedented view of change across the globe. We're combining this imaging capability with state-of-the-art big-data and cloud-computing technologies to enable easy access to this data by those who need it most. (Planet Labs 2013)

Planet Labs launched twenty-eight 3-unit CubeSats into low earth orbit in January 2014. The satellites were carried to the International Space Station and then deployed in pairs over a number of weeks (Vance 2014). The group of satellites was dubbed "Flock 1" by Planet Labs.

1. Reverse Engineering the Camera/Sensor Characteristics

Little public information was available about the imaging sensor on the Flock 1 satellites. Using information from Planet Labs' previous Dove-1 and

Dove-2 technology demonstration missions, rough estimates of the Flock 1 capability were estimated assuming the satellites are similar.

Table 2. Planet Labs Sensor Data

Parameter	Value	Source
Optic Aperture (Dove-2)	.09 meters (90 mm)	(Planet Labs 2013)
GSD (Dove-2)	4.4 meters at 575 kilometers altitude	(Planet Labs 2013)
Focal Plane Array Height (estimate)	1,654 pixels	(Werner 2013)
Focal Plane Array Width (estimate)	2,253 pixels	(Werner 2013)

The satellites are only nadir pointing, based on a description of the Dove-2 Guidance, Navigation and Control (GNC) subsystem attempting to mimic permanent magnets, which usually provide roughly nadir pointing (Planet Labs 2013). Assuming the satellites are nadir pointing, then range is equal to altitude. Therefore, angular resolution is calculated:

$$GSD = Range * \Delta\theta$$
$$or$$
$$\Delta\theta = \frac{GSD}{Range} = \frac{4.4meters}{575,000meters} = 7.6522*10^{-6}$$

(Olsen 2007)

A sample image provided for Dove-1 showed 1654 pixels high by 2253 pixels wide (Werner 2013). Using the height, the field of view of the sensor was calculated as:

$$FOV = \Delta\theta * 1654 = 7.6522*10^{-6}*1654 = 0.012657 radians = 0.725175 \text{degrees}$$

The above calculation assumed the sample image was a full size image from the sensor and not a “chip” or subset of the original image. It also assumed the Flock 1 satellites had the same sensor as the Dove-2 satellite. The sensor

was assumed to cover the visible bands from approximately 450 to 800 nanometers.

2. Planet Labs Funding Information

Planet Labs is a privately held company and has not publically stated the costs for their satellite development, launch or operations. The company has received two rounds of venture funding. Table 3 shows the funding raised by Planet Labs according to Securities and Exchange Commission filings, which is about $68.5M total.

Table 3. Planet Labs Funding Information (from U.S. Securities and Exchange Commission 2014)

Date	Funding Amount	SEC Filing #
7/23/2013	$3,200,000	0001543165-13-000002
7/23/2013	$13,416,173	0001543165-13-000003
1/2/2014	51,882,764	0001543165-14-000001

According to Space News, the second round of funding will be used to build and launch another 72 satellites over the course of 12 months (de Selding 2014). Each satellite is expected to last one to two years (Werner 2014).

C. WORLDVIEW-2

WorldView-2 is the first commercial multi-spectral imager. A picture of the satellite in development is shown in Figure 6. It takes panchromatic images in the 450 to 800 nano-meter band. It has six visible color sensor bands between 400 and 745 nano-meters and two bands in the near-infrared from 770 to 1040 nano-meters. The resolution is 0.46 meters using panchromatic and 1.85 meters in the multispectral bands at nadir. It has a dynamic range of 11 bits per pixel,

meaning it can discern 2^{11}or 2048 different levels of light. It can image 1,000,000 km^2 per day with a NIIRS of 5.0 or greater (DigitalGlobe 2013).

The sensor can retarget up to 200 km in 10 seconds due to the 3.86 degrees per second slew rate of the bus. The agility of the spacecraft allows for stereo imaging, which means taking two images of a single location from different look angles. In stereo mode it can collect 63 x 112 km on a single pass. (DigitalGlobe 2013) WorldView-1 takes up to 524 gigabits of data per obit, which is stored on 2199 gigabit solid state drive with error detection and correction (DigitalGlobe 2013). The WorldView-2 camera has a focal length of 13.311 meters and a pixel size of 8 micro-meters(Exelis Visual Information Solutions 2014). DigitialGlobe has 11 ground stations (Kindelspire 2012).

Figure 6. WorldView-2 in Development (from Ball Aerospace & Technologies Corp. 2013)

The total cost for WorldView-2 including ground infrastructure was around $400 million. No U.S. government funding was provided for development of the imaging satellite, which was a first at the time of development (McCoy 2007). WorldView-2 was launched on a Delta II rocket. The cost of that launch was not available,; however, a Delta II launch for NASA's Ice, Cloud and Land Elevation

Satellite (ICESat)-2 mission to a similar near-polar orbit cost $96.6M in 2013. (Kyle 2014)

D. COST

Since little information was known about either system, the cost model described in section III.C was not used and a simple cost model was created. A number of assumptions were made that could drastically change the resulting cost. The total amount for the system was divided by the number of satellites produced to get a cost per satellite. This was multiplied by the number of satellites required for the scenario to get the total cost. The cost calculations are shown in Table 4.

Planet Labs' total reported funding of $68,500,000 was divided by the number of satellites built and launched to get a cost per satellite of $685,000. No learning curve was applied, so it is likely the total cost of the later satellites is significantly lower. STK calculated the lifetime of each satellite as 190 days given a cross area of 338 centimeters, which the author estimated based on Planet Labs' pictures of the satellites. A total of 390 satellites were required to maintain constant capability on orbit for 7.25 years. The total cost for the scenario was $267,150,000.

DigitalGlobe's total reported funding for the development and operation of WorldView-2 was $400,000,000. The added cost of a Delta-II rocket to launch it was approximately $96,600,000. The advertised lifetime was 7.25 years. The total cost for the scenario was $496,600,000.

The cost to build and operate a combined constellation of twenty-eight Flock-1 satellites and one WorldView-2 satellite was calculated as a sum of the previous two system costs, which was $763,750,000.

Table 4. ISR Scenario Cost Calculations

	Planet Labs (28)	World View 2	Both
Total funding/cost	$ 68,500,000	$ 400,000,000	
# of satellites produced	100	1	
Cost per satellite	$ 685,000	$ 400,000,000	
Launch cost per satellite	included	$ 96,600,000	
Scenario time (years)	7.25	7.25	7.25
Sat life (years)	0.520547945	7.25	
# of sats in constellation	28	1	
# of sats needed	390	1	
Total cost	$ 267,150,000	$ 496,600,000	$ 763,750,000

E. STK SCENARIO

1. Flock-1 Satellites

All 28 Flock-1 satellites built by Planet Labs were imported from STK's Data Federate that takes orbit data from spacetrack.org. A simple sensor was created based on the section B.1 analysis of the field of view and was attached to all 28 satellites. The sensor was restricted to operations when the target was in full sun because it only operates in the visible wavelengths, where the reflection of sunlight off the target is the primary source of radiation detected by the sensor.

2. WorldView-2

WorldView-2 was imported from STK's Data Federate. The panchromatic and multispectral sensors were created based on the information in section C. The sensors were set to "targeted sensor pointing" mode to allow the sensors to slew within the limits of each space vehicle. The targeted sensor pointing mode is more realistic than simple nadir pointing, however it is limited in that continually points the sensor toward the center of the target area instead of maximizing coverage of the entire area. A more skilled STK user likely could employ a different targeting method resulting in better coverage.

3. Target Area

An STK "target area" for the North East was created. It ranged 10 degrees latitude from north to south, and 15 degrees longitude from east to west. An STK "coverage area," used to generate statistics on satellite performance, was created based on the North East target area. The coverage area was divided into sample points 25 kilometers apart that were used to calculate statistics. Using a distance of 5 kilometers resulted in more grid points, and therefore longer calculation times, however, the difference in results was less than one percent.

4. Figures of Merit

Next STK "figures of merit" were added to the coverage area as a means to extract data from the simulation. Figures of merit were added for the average number of accesses per day; the average revisit time; the maximum revisit time; the minimum ground sample distance; the minimum revisit time; and the total number of accesses per day. The figures of merit correspond to the Measures of Performance as shown in Table 1.

5. Limitations of the STK scenario

As with any modeling and simulation tool, it was nearly impossible to fully represent a real life scenario. One major limitation was the computing resources required. The scenario timeline was set at only two weeks since that was the amount of time that could be simulated overnight on the available desktop computer. A longer scenario timeline would provide slightly more realistic statistics as the figures of merit would be averaged over a longer timeframe.

Limited information was available on the satellite systems, especially Planet Labs. A number of assumptions had to be made in representing the systems in STK. For example, Planet Labs' satellites are assumed to be only nadir pointing without the ability to slew to image target areas not along the ground track. This was a major performance penalty as compared to WorldView-

2. Additional information on the systems could lead to significantly different results.

Satellite and ground station limitations were not taken into account. The analysis focused primarily on the sensors' ability to take images. The maximum onboard data storage, downlink throughput, and access to ground stations were not factored into the scenario. The scenario could be more realistic if these limits were enforced using STK's concept called "chains" if more time and expertise were available.

F. EFFECTIVENESS

The STK scenario was run in a number of configurations. First only Flock-1 satellites were studied. Next only WorldView-2 was studied. Finally, a combination of Flock-1 and WorldView-2 was studied. The results for each run are described below.

1. Flock 1 only

First only Flock-1 satellite performance was calculated using STK. The Percent Coverage graph from STK shown in Figure 7 depicts the percentage of the coverage area that is covered by any active Flock-1 satellite in red. Since the target area is much larger than the footprint of the sensor on each satellite, the percentage covered at one time is generally less than one percent and is not visible in the graph. The total accumulated percentage of the area covered is shown in blue.

The Percent Coverage report provides the raw information used to create the graph. Flock-1 covered 95.16% of the target area over the course of the two week scenario. The total coverage percentage was divided by the scenario time to find the average cumulative coverage per day was 6.80%.

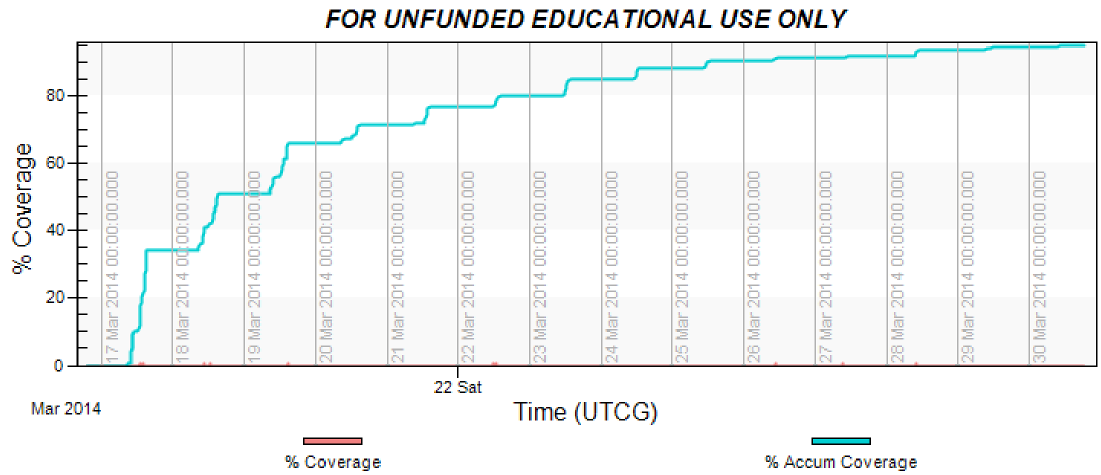

Figure 7. Flock-1 Percent Coverage Over Time

Figure 8 shows the average number of accesses per day over the target area. STK calculated this as:

> "The total number of accesses over the entire coverage interval divided by the number of days in the coverage interval."

The grid statistics report calculated the average number of accesses as 0.31 per day.

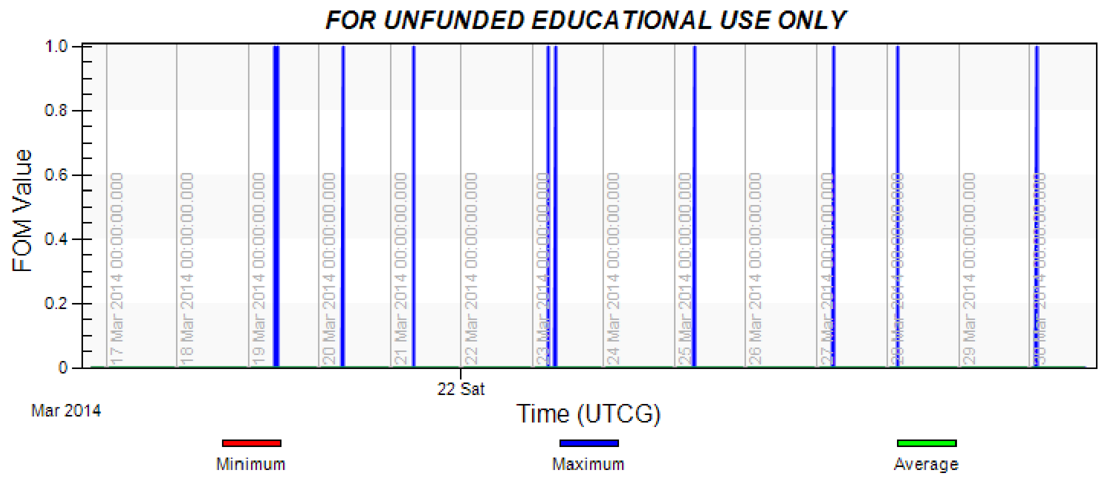

Figure 8. Flock-1 Average Number of Accesses Per Day

The average revisit rate, or the time between accesses, is shown in Figure 9. The grid statistics report calculated the average revisit rate was 62.12 hours.

The maximum revisit rate was 336 hours or 14 days, which means that some grid points in the target area were not visited during the scenario.

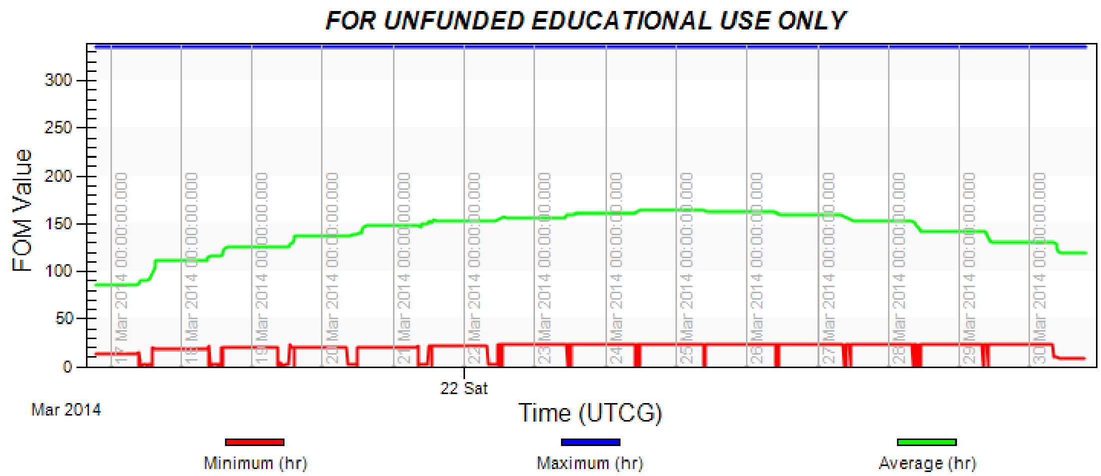

Figure 9. Flock-1 Average Revisit Rate (hours)

Figure 10 shows the minimum ground sample distance achieved by a satellite sensor over the target area. STK defined the ground sample distance as:

> The Ground Sample Distance is the smallest size of an object on the ground that can be detected by the sensor. It applies to facilities, places, and targets, and is based upon the access geometry and the physical attributes of the sensor.

The grid statistics report calculated the minimum ground sample distance as 3.01 meters. The minimum and maximum values were very close to the average since the Flock-1 satellites were always nadir pointing.

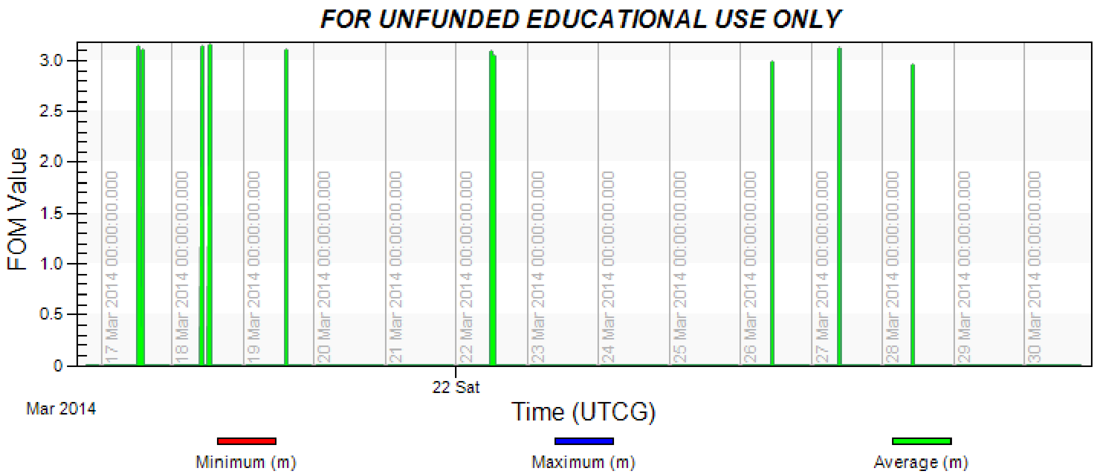

Figure 10. Flock-1 Minimum Ground Sample Distance (meters)

Figure 11 shows the average number of total accesses by longitude. There is some variation across longitudes due to the timing of the two week scenario. If the scenario had run across a longer timeframe, the value for each longitude would be nearly identical.

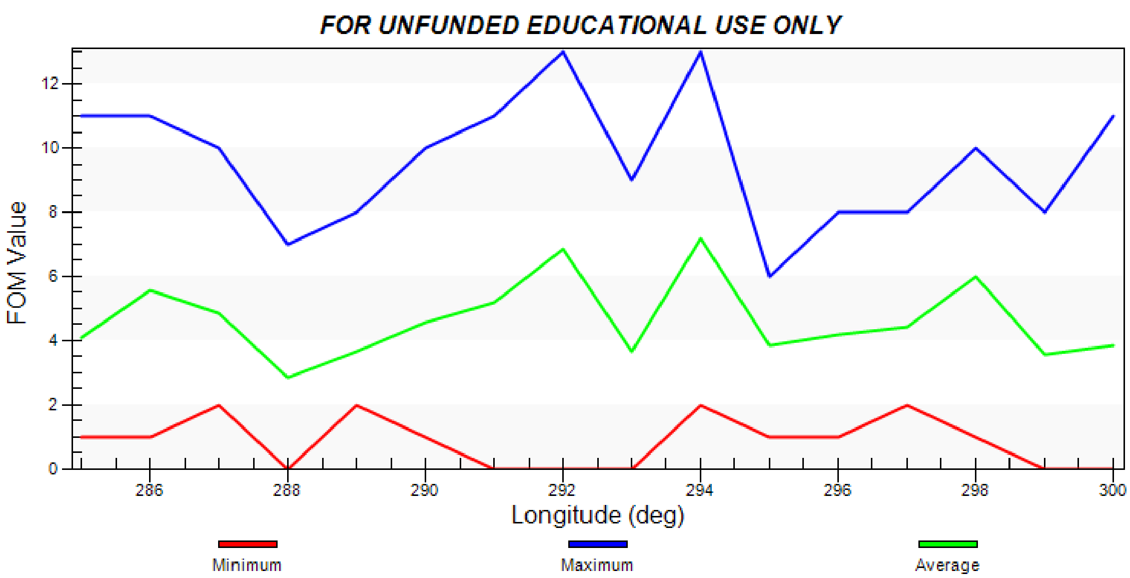

Figure 11. Flock-1 Total Accesses by Longitude

The average total number of access by latitude is shown in Figure 12. The values generally increase as the latitude increases. This is consistent with

orbital mechanics, where the maximum coverage is provided at the latitude that equals the spacecraft's inclination. The Flock-1 satellites were all at nearly 51.6 degrees inclination.

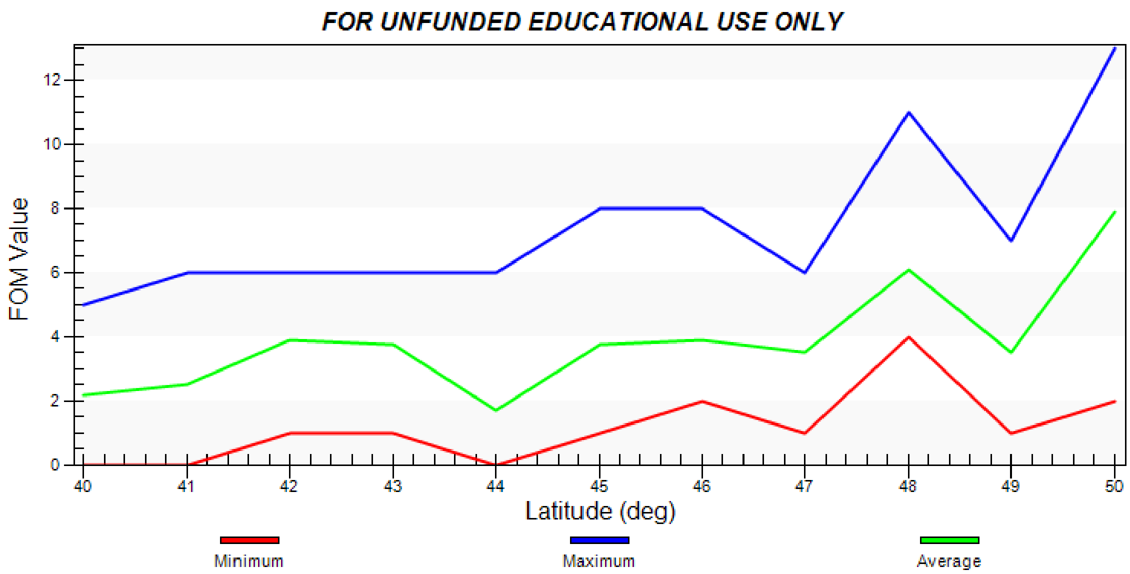

Figure 12. Flock-1 Total Accesses by Latitude

2. Worldview-2

WorldView-2 covered 93.01% of the target area over 14 days. The total coverage percentage was divided by 14 to find the average cumulative coverage per day was 6.64%.

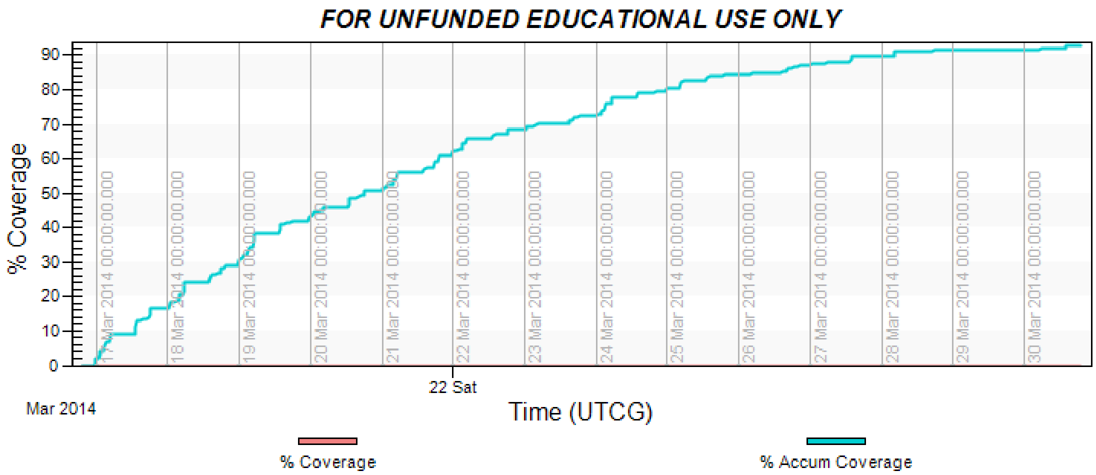

Figure 13. Worldview-2 Percent Coverage Over Time

The grid statistics report calculated the average number of accesses as 1.52 per day.

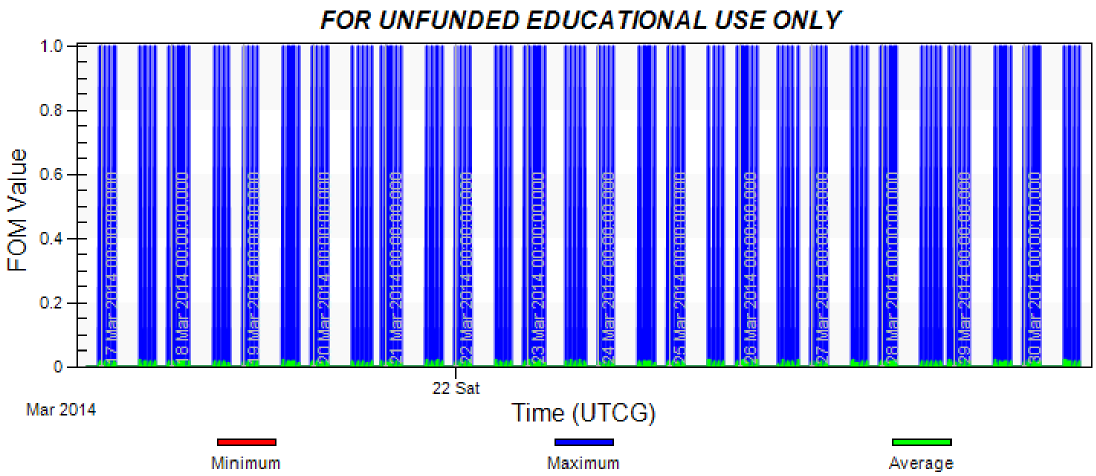

Figure 14. WorldView-2 Average Number of Accesses Per Day

The average revisit rate is shown in Figure 15. The grid statistics report calculated the average revisit rate was 16.81 hours. The average maximum revisit rate was 29.51 hours, and the average minimum revisit rate was 8.81 hours.

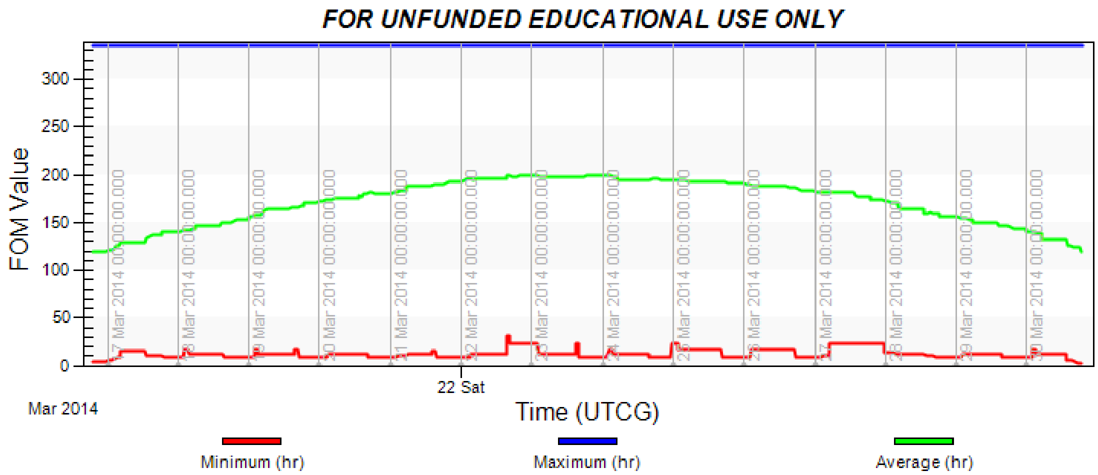

Figure 15. WorldView-2 Average Revisit Rate (hours)

Figure 16 shows the minimum ground sample distance achieved by either of the WorldView-2 sensors over the target area. The satellite points toward the target area, so the ground sample distance is initially high and then decreases while it approaches the center of the target, performance comes close to the system design of 0.50 meters close to nadir, and then the ground sample distance increases as the satellite leaves the target area. While the graph shows these values, any ground sample distance greater than 10 meters was not included in the calculations because a "satisfaction" constraint was set. The grid statistics report calculated the average minimum ground sample distance as 2.93 meters.

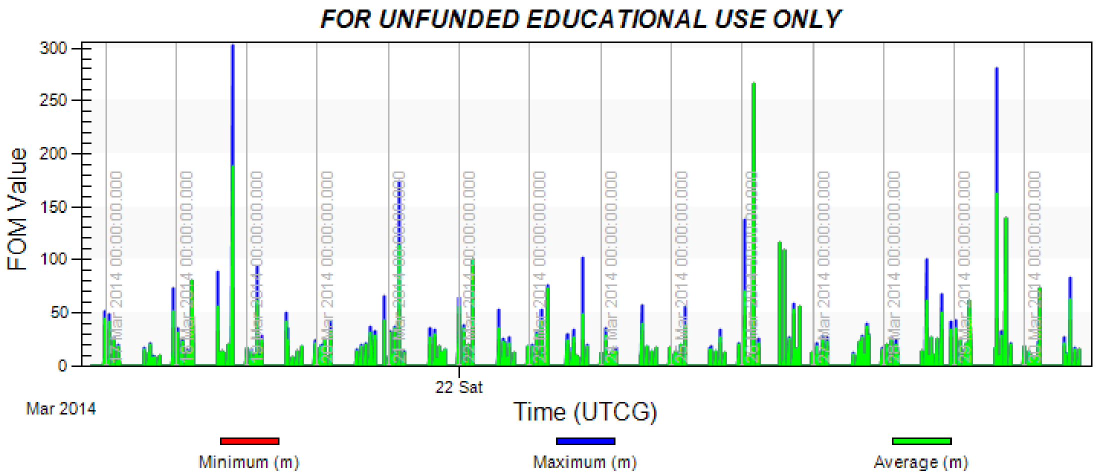

Figure 16. WorldView-2 Minimum Ground Sample Distance

Figure 17 shows the average number of total accesses by longitude. There is some variation across longitudes due to the timing of the two week scenario. Since the satellite was allowed to slew to point toward the center of the target, the longitude of the center of the target received more accesses.

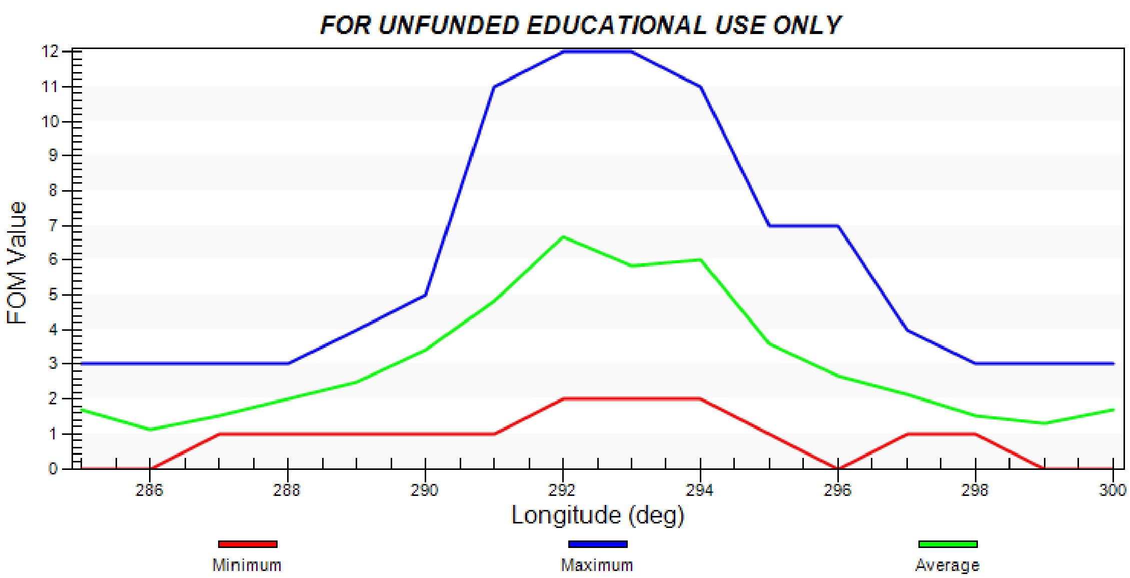

Figure 17. WorldView-2 Total Accesses by Longitude

The average total number of access by latitude is shown in Figure 18. The values generally increase as the latitude increases.

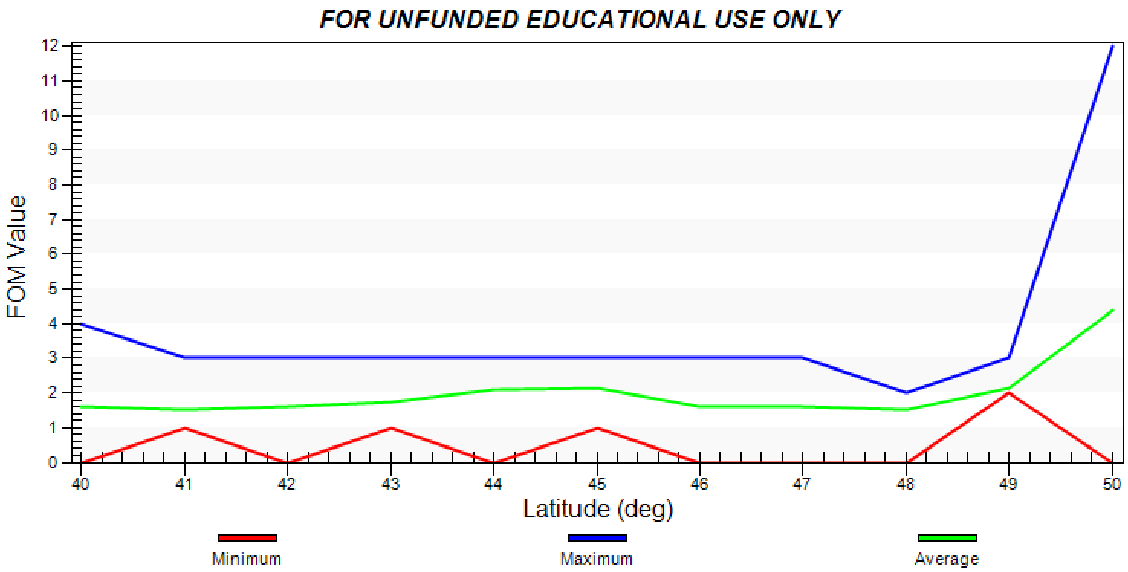

Figure 18. WorldView-2 Total Accesses by Latitude

3. Flock-1 and WorldView-2 Combined

The combination of Flock-1 and WorldView-2 covered 100% of the target area over 2.28 days. The total coverage percentage was divided by 2.28 to find the average cumulative coverage per day was 43.89%. This was the same as WorldView-2 by itself.

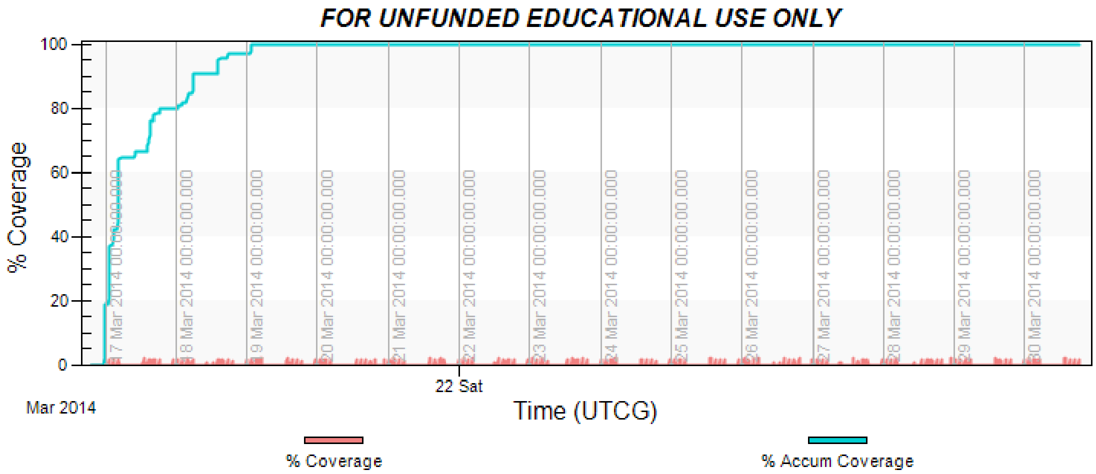

Figure 19. Flock-1 and WorldView-2 Percent Coverage Over Time

The average revisit rate is shown in Figure 20. The grid statistics report calculated the average revisit rate was 14.33 hours. The average maximum revisit rate was 28.29 hours, and the average minimum revisit rate was 6.71 hours.

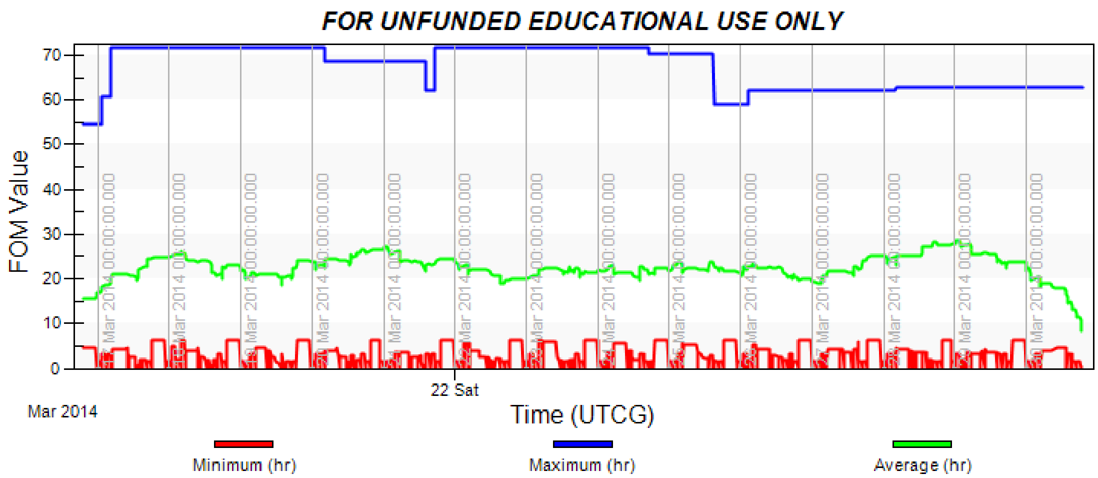

Figure 20. Flock-1 and WorldView-2 Average Revisit Rate (hours)

The grid statistics report calculated the average number of accesses as 1.83 per day. Figure 20 shows the revisit rate over time.

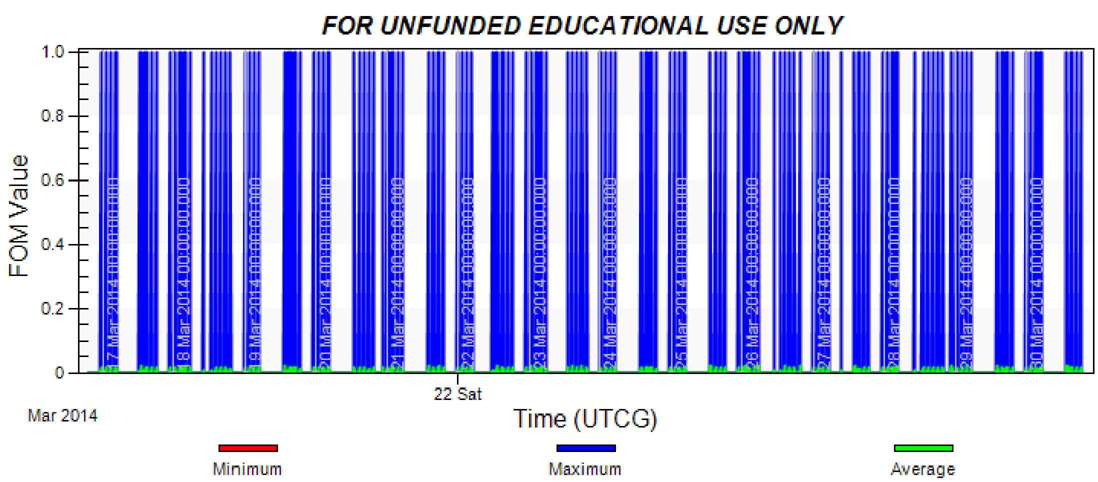

Figure 21. Flock-1 and WorldView-2 Average Number of Accesses Per Day

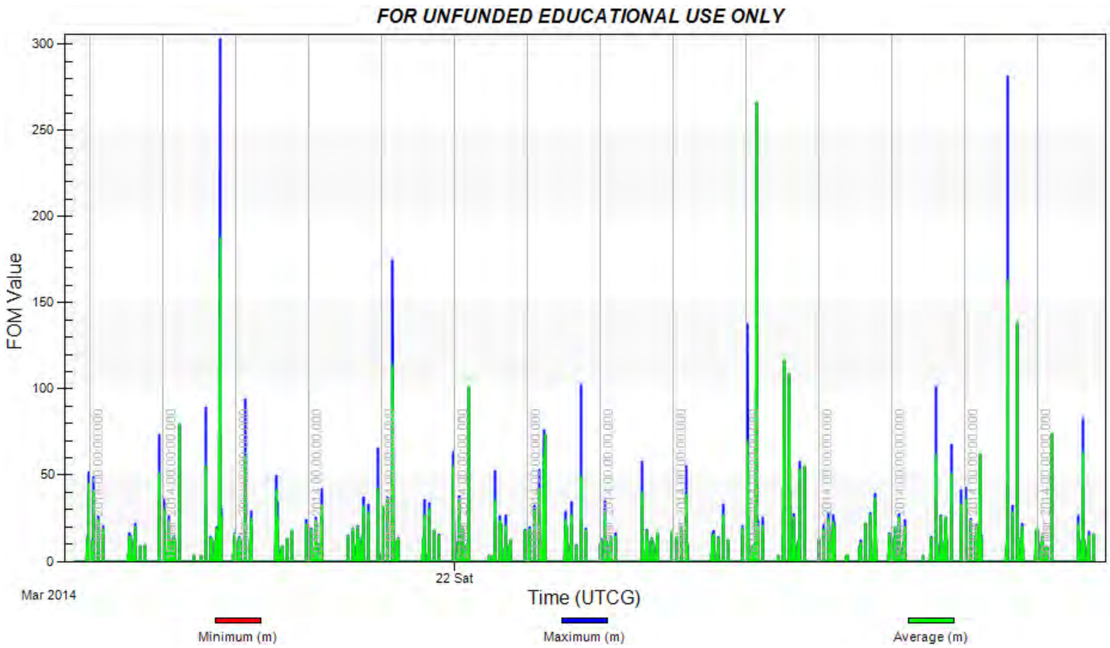

Figure 22. Flock-1 and WorldView-2 Minimum Ground Sample Distance

Figure 23 shows the average number of total accesses by longitude. There is some variation across longitudes due to the timing of the two-week scenario. Since WorldView-2 was allowed to point toward the center of the target, the longitude of the center of the target received more accesses.

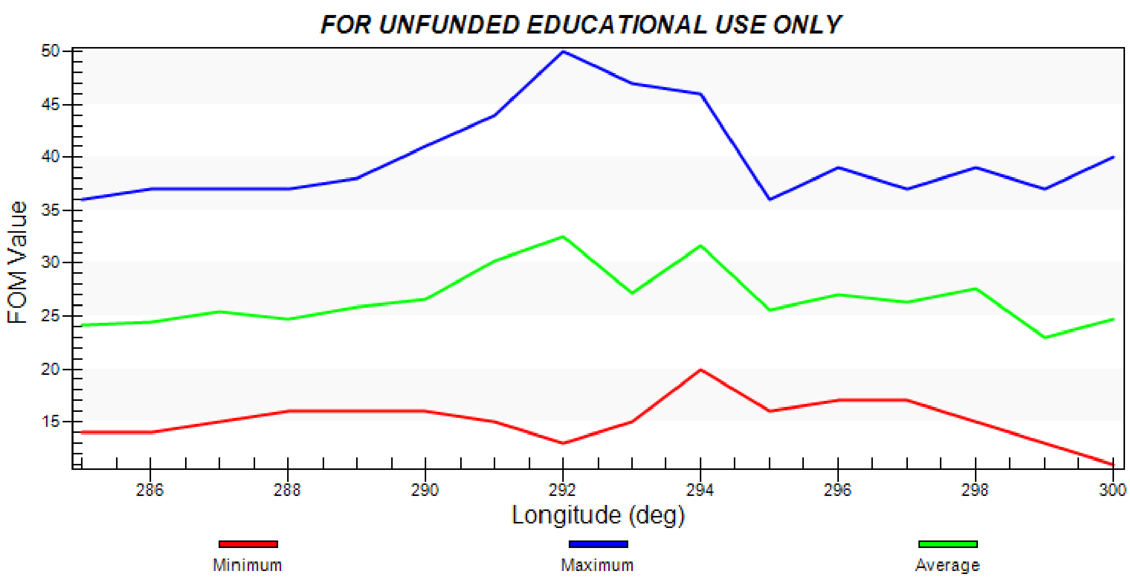

Figure 23. Flock-1 and WorldView-2 Total Accesses by Longitude

The average total number of accesses by latitude is shown in Figure 24. The values generally increase as the latitude increases since WorldView-2 and the Flock-1 satellites all have an inclination greater than 50 degrees.

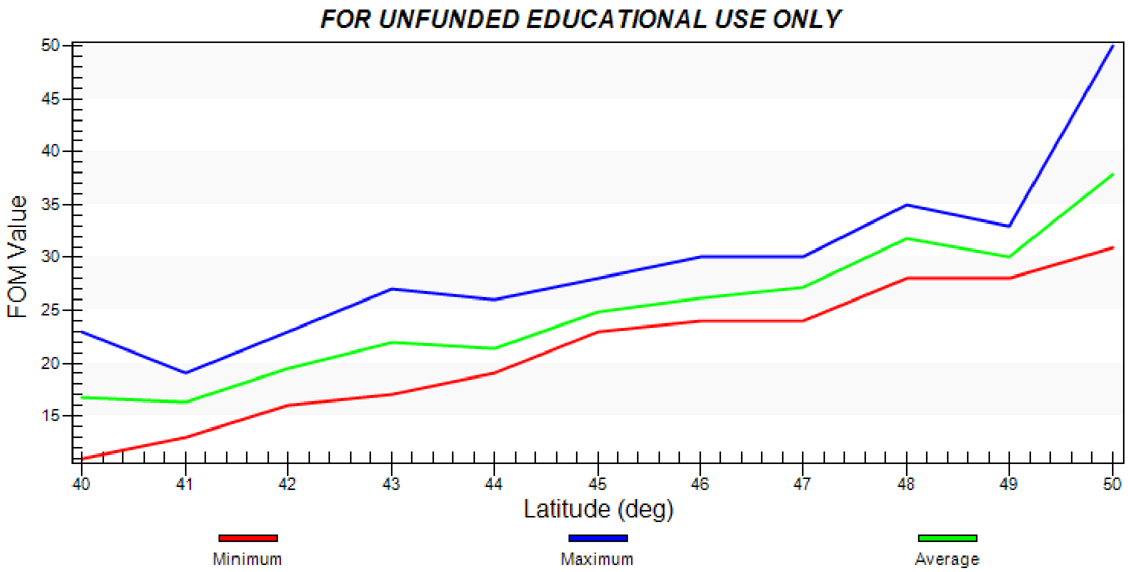

Figure 24. Flock-1 and WorldView-2 Total Accesses by Latitude

G. COST EFFECTIVENESS

Satellite system cost and effectiveness information were entered into the cost effectiveness model to compare the system options. A basic cost model for each satellite was developed and described in section D. A swing weight matrix was developed to calculate effectiveness. The performance of each system was modeled using STK and entered in the model shown in Table 1. Finally, the effectiveness of each system option was graphed against the system cost as shown in Figure 25.

Planet Labs' twenty-eight Flock-1 satellites achieved an effectiveness of 34% at a cost of $267,150,000. DigitalGlobe's WorldView-2 satellite achieved an

effectiveness of 36% at a cost of $496,600,000. The combination of Flock-1 and WorldView-2 achieved an effectiveness of 64% at a total cost of $763,750,000.

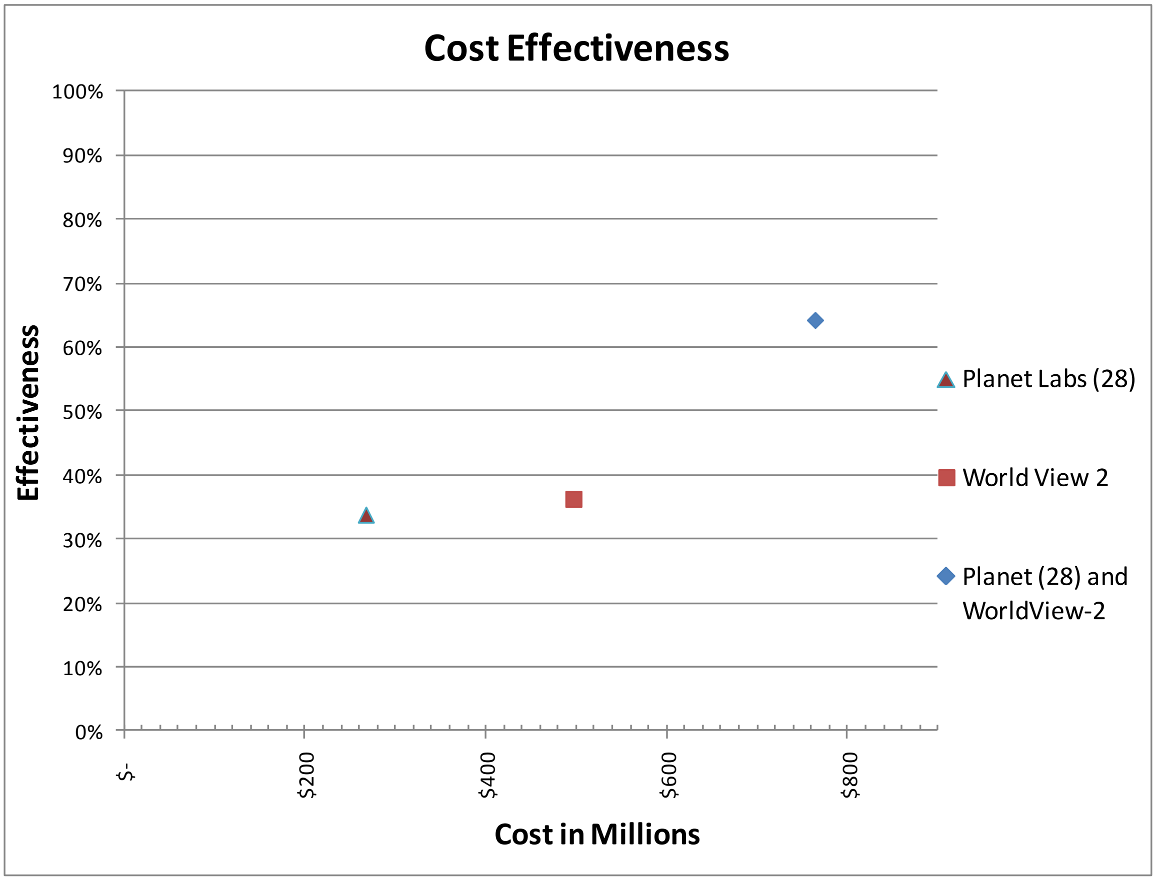

Figure 25. ISR Scenario Cost Effectiveness Results

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V. ENVIRONMENTAL MONITORING

A. SCENARIO

Environmental Monitoring payloads provide a wealth of information about the ocean and littoral regions for naval forces. Radar altimeters such as TOPEX/ Poseidon and Jason-2 measure the sea surface height as well as wave height and wind speed. The next mission, another NASA and France collaboration called Jason-3, is planned for launch in 2015 (Jet Propulsion Laboratory 2014). The Navy planned to acquire the Geodetic/geophysical Satellite (GEOSAT) Follow-On 2 (GFO-2) altimetry satellite in 2013, but the program was deferred and will not be launched until at least 2017 (U.S. Navy 2012). The Navy has also invested in a Small Business Innovative Research effort to develop a radar altimeter payload for a 3-unit CubeSat (U.S. Government 2014).

The environmental monitoring scenario assumed budgetary or technical challenges continued to delay Jason-3 (Morello 2012). The Navy was forced to acquire its own altimetry capability. The option to continue the GFO-2 program was compared against a multi-satellite system based on the newly developed CubeSat altimetry payload. This scenario represents the Environmental Monitoring component of Space Force Enhancement from Joint Publication 3-14.

Similar to the ISR scenario, the author modified the generic objectives hierarchy from Section III.D.1 to best fit the environmental monitoring scenario. The high level objectives were broken down into measurable components. Thresholds and objectives were established, and the swing weight matrix described in section III.D.3 was applied to the scenario. The end result was captured in Microsoft Excel and is shown in Table 5.

Table 5. Environmental Monitoring Scenario Effectivess Model

Measure of Effectiveness	Measure of Performane	Metrics	Threshold	Objective	Importance	Var. %	Var. bin
Payload performance	Radar Range Error (cm)	From Literature/Assumption	5	1	Med	75%	High
	Orbit Determination Error (cm)	From Literature/Assumption	40	2	High	74%	High
Persistence	Percent of Earth revisited	STK FOM: Access Separation	5%	100%	High	26%	Low
Resiliency	Capability with one lost satellite	1 - Single sat % of constellation	0%	98%	Low	77%	High
	Capability with one lost ground station	1 - Single ground station % of system	0%	98%	Low	13%	Low

B. GFO-2

The GEOSAT Follow-On 1 (GFO-1) satellite was launched in 1998 to continue the data collection from the GEOSAT Exact Repeat Orbit mission. The satellite launched in February 1998 and became operational in November 2000. The GFO-2 mission was planned to continue the capability (Finklestein 2010). SPAWAR awarded Ball Aerospace and Technology Corporation contract N00039-10-D-0068 to develop the GFO-2 satellite in April 2010. The contract called for three centimeter precision and a lifetime of six years. The total cost of the contract if all options were exercised was estimated at $499,625,341 (Space and Naval Warfare Systems Command 2010).

C. NANO-SATELLITE ALTIMETER

A nano-satellite based altimeter mission poses a number of technical challenges. Assuming any nano-satellites would be launched in the near future would be ride-share or piggy-back payloads, an exact repeat orbit would be unlikely. Most nano-satellites have been flown at lower altitudes than previous radar altimeter payloads. Orbit determination for satellites is generally harder at lower altitudes, and orbit determination error is the primary source of error in

altimetry measurements. Any potential nano-satellite mission would be very different from traditional altimetry missions.

Since the original Skylab experiments in 1973, nearly all altimetry missions have used an exact repeat orbit between 10 and 35 days (Rosmorduc et al. 2009). Jacobs et al. suggested that “while data may be obtained from an altimeter that is not in an exact repeat orbit, the quality and quantity of useful data are significantly diminished.” Using a ground track that doesn’t line up with previous systems will require significant time to establish enough statistics for reliable results, possibly years’ worth of data. If the new ground track overlaps a previous system’s track, a relatively small amount of data can be used to combine data and produce quality results quickly (Jacobs et al. 1999) even if the new ground track is not a repeat orbit (Jacobs and Mitchell 1997). That said, a dozen or two micro satellites launched as piggyback payloads could provide good temporal and spatial resolution if done in conjunction with a high accuracy mission (Wilson et al. 2012). Small satellite designs were already considered by Johns Hopkins Applied Physics Laboratory (Kilgus, Hoffman and Frain 1989), Surrey Space Center (Zheng 1999) and Thales Alenia Space (Richard et al. 2008). A 6U CubeSat concept was proposed by Australia’s Defense Science and Technology Organization (Stacy 2012).

Sea surface height is calculated as the difference between the satellite altitude and the range determined by the altimeter. Therefore, precise orbit determination is a key factor in system accuracy (EUMETSAT 2010). Most altimeter missions have launched to orbits above 800 kilometers altitude because the Earth’s gravity potential is now well understood at lower altitudes (Rosmorduc et al. 2009). Previous large satellite missions used laser ranging, DORIS, GPS, or a combination for precise orbit determination (Allan 2006). Nano-satellite sized DORIS receivers (Barnum et al. 2012) and laser retro-reflectors (Wayne, Lovern and Obukhov 2014) have been shown to be feasible and are in development, and GPS receivers have already flown on multiple nano-satellite missions.

A notional 6U CubeSat design was considered. It was assumed the radar altimeter required 1U, the DORIS receiver 1U, and the laser retro-reflectors took 1U. This left 3U of volume for the bus, which was assumed to include the GPS receiver as most recent nano-satellite bus designs have. It was assumed four ground stations were required to control the satellite and retrieve the data.

D. COST

The cost model described in section III.C was used to estimate the cost of the NanoSat Altimeter. While the altimeter was proposed to fit within a 3U CubeSat (U.S. Government 2014), the author assumed a 6U mission would be required to allow volume for a laser retro-reflector and a DORIS receiver to achieve precise orbit determination. At double the volume and mass, the author assumed the cost would also double when going from a 3U to a 6U CubeSat in the cost model. The cost for launching a 6U CubeSat was also assumed to be double the cost of a 3U. A requirement for four dedicated ground stations was assumed. The additional resources required to modify naval oceanographic models to account for non-repeat orbit data were assumed to be four government engineers per year.

A grouping of four CubeSats was evaluated. Each satellite was assumed to have a functional lifetime of one year. Therefore, the six year scenario required twenty-four satellites. While building such a large number would likely see production efficiencies, no learning-curve discount was assumed in the cost model. The original cost model was built to support a five-year cost projection and was not easily modified. The costs for the six-year scenario were only spread over five years. If the cost model were updated to spread the costs over six years, there would likely be minor cost differences due to rate of inflation and other year dependent factors. The SPAWAR cost model reported a total program cost of $109.2M for a CubeSat altimetry program. Changing any of the assumptions could drastically change the cost estimate.

The Navy's total estimated cost of GFO-2 was $499.6M and included the cost of a second satellite. This estimated cost was divided by two to get a cost of $249.8M for one satellite. The cost was adjusted for inflation from FY10 to FY13 dollars to match the nano-satellite cost model, resulting in an FY13 cost of $265.7M. This cost included the satellite production, launch and ground station equipment required. The advertised satellite lifetime was six years and assumed to be accurate. Since the estimated contract cost was all-inclusive, a detailed cost model was not used. The cost of both the GFO-2 and CubeSat Altimeter option are shown in Table 6.

Table 6. Environmental Monitoring Scenario Cost Calculations

	GFO-2	Nanosat Altimeter
Cost per satellite	$ 265,689,164	$ 2,326,560
Launch cost per satellite	$ -	$ 588,813
Scenario time (years)	6	6
Sat life (years)	6	1
# of sats in constellation	1	4
# of sats needed	1	24
Total satellite costs	$ 265,689,164	From SPAWAR model
Total cost	$ 265,689,164	$ 109,159,000

E. STK SCENARIO

An STK scenario was created to model the Environmental Monitoring scenario. The scenario timeframe was 28 days long. Satellite objects were created for GFO-2 and four Nano-satellite Altimeters. The scenario is shown in Figure 26. Details of each satellite are described below.

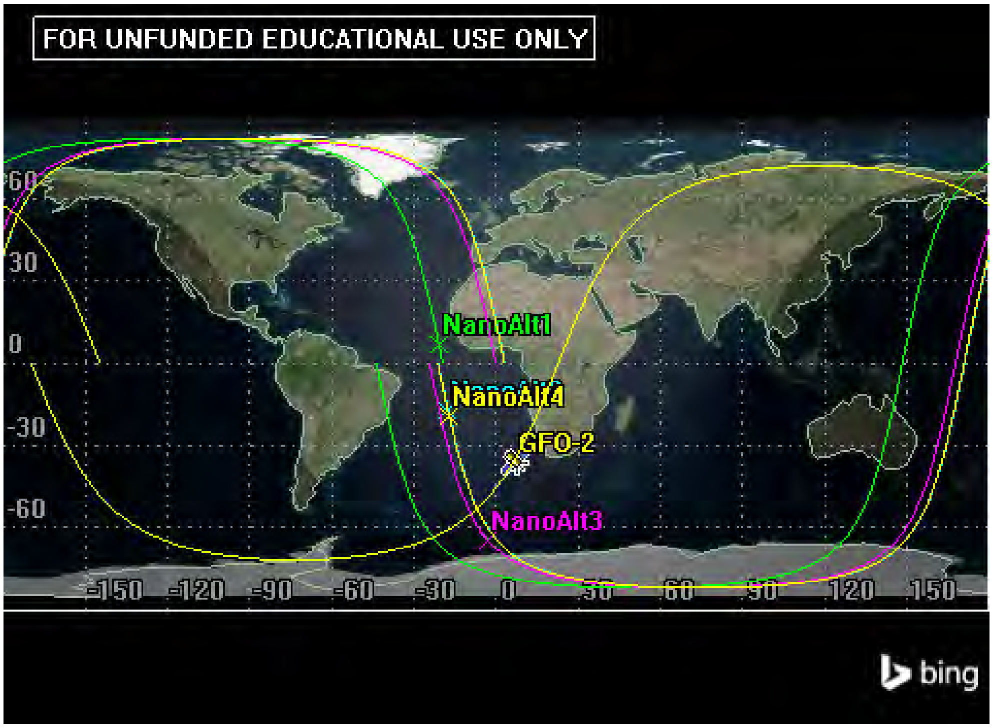

Figure 26. Environmental Monitoring STK Scenario

1. GFO-2

A satellite object was created and given an 800 kilometer orbit at 108 degrees inclination, the same as the GEOSAT Follow On-1 (GFO-1) satellite (National Aeronautics and Space Administration 2012). A simple conic sensor with a swath width of 20 kilometers (Rosmorduc, et al. 2009) was attached to the satellite and pointed at nadir.

2. Nano-satellite Altimeter

The orbit of four CubeSats launched by a Dnepr rocket in June 2014 were imported from STK's Data Federate. The 620 kilometer circular orbit at an inclination of 98 degrees (Krebs 2014) was close to the inclination of the desired orbit of GFO-2. A simple conic sensor was attached to each satellite and pointed at nadir. The frequency was assumed to be 13.5 GHz, the same as GFO-1. The antenna was assumed to be 60 centimeters wide, which would be a likely size for a deployable antenna on a 6U CubeSat. The delta-Theta or angle of the radar

sensor was calculated as 0.0185 radians using $\Delta\theta = \lambda/L$ (Olsen 2007) where lambda was the wavelength of 0.031 meters (Finklestein 2010) and the antenna length L was 0.6 meters.

3. Global Coverage Area

An STK coverage area was created to cover the entire Earth. A "global grid" type coverage area does not require a target area, unlike the ISR scenario. The coverage area was divided into sample points 100 kilometers apart that were used to calculate statistics.

4. Figures of Merit

Next STK figures of merit were added to the coverage area to extract data from the simulation. An "Access Separation" figure of merit was defined. "Access Separation detects periods of time when grid points have multiple access periods within a specified time range of each other" (Analytical Graphics, Inc. 2014). The range was defined as at least 16 days separation but no more than 18 days to be close to the repeat rate for GFO-2. The "Percent Satisfied" report provided a percentage of the number of grid points that achieved that access separation. The intent of the measurement was to find how often the Nano-Satellite Altimeter swarm revisited grid points on a time scale similar to GFO.

5. Limitations of the STK scenario

The global coverage was calculated on a grid of points separated by 100 kilometers, which is nearly ten times the swath width of the radar altimeters. Using more grid points would give a more accurate representation. Moving to a 10 kilometer grid would mean a 100 fold increase in the number of grid point calculations. The scenario took many hours to calculate using the 100 kilometer grid with a quad-core desktop computer. A 10 kilometer grid was not feasible given the computing resources available.

Limitations of the satellite and ground station were not taken into account. The analysis focused on ground track coverage. Maximum onboard storage,

downlink throughput, power limitations and other constraints were not factored into the scenario.

F. EFFECTIVENESS

The measures of effectiveness for each satellite system were calculated or taken from literature. Calculating the radar altimeter payload performance or system orbit error was out of scope for this thesis. Each satellite's coverage of the Earth was modeled in STK. The persistence of each system was calculated based on the number of satellites and ground stations in the system. The calculation of the total effectiveness required a number of assumptions that must be verified by experts prior to using this scenario for decision making purposes.

1. GFO-2

GFO-2 was assumed to meet the performance specification of three centimeter total error published by SPAWAR (Space and Naval Warfare Systems Command 2010). This error was assumed to be one centimeter of radar range error and two centimeters of orbit determination error. This resulted in a scaled score of 100% for both measures as they met the objective values.

STK did not properly model GFO-2 in an exact repeat orbit, so satellite coverage was estimated using Microsoft Excel. The radar swath width was multiplied by the average radius of the Earth to find the number of square kilometers covered per orbit. This number was then multiplied by 244 (National Oceanographic Data Center Laboratory for Satellite Altimetry 1997), the number of revolutions before GFO-2 started repeating the orbit. This result was 224,378,677 square kilometers, but did not account for the fact that the ground track for each revolution crossed each earlier ground track twice. The ground tracks crossed a total of 59,292 times over the first 244 revolutions. For simplicity, the cross over area was assumed to be a square of the radar swath width which was 527 square kilometers. The resulting crossed over area of 31,221,290 was subtracted from 224,378,677 since it was counted twice. The

adjusted number of square kilometers covered was 193,157,387, or 37.786% of the total surface area of the Earth.

Resiliency of the constellation of satellites was defined as the percentage of satellite capability lost if one satellite was lost. This was calculated as the number of satellites minus one divided by the number of satellites. Since there was only one satellite, GFO-2's raw score was zero. The resiliency of the ground was calculated in the same manner, but replacing satellites with the number of ground stations. GFO-2 was assumed to use the Air Force Satellite Control Network, which has eight Remote Tracking Stations around the globe to communicate with satellites (Hodges and Woll 2008). The resulting raw score was 88%.

2. Nano-satellite Altimeter

A previous study suggested a 40 centimeter per side micro-satellite could achieve accuracy close to the five centimeter mark of the Topex/Poseiden mission (Richard, et al. 2008). A 6U CubeSat would be slightly small and have less power, so the author assumed it could only achieve the performance of the original GEOSAT. Range error was entered as four centimeters and orbit error as 30 centimeters (Rosmorduc, et al. 2009). This resulted in a scaled score of 25% for range error and 26% for orbit error.

The STK scenario was used to calculate the percent of the Earth that was revisited. The result for a revisit between 16 and 18 days by one of the four Nano-satellite Altimeters was 13.24%. To see the potential impact of a wider tolerance, the author also calculated the percent revisited between 10 and 20 days, and the result was 44.51%.

With four satellites, the raw score for the resiliency of the Nano-satellite Altimeter constellation was calculated at 75%. The author assumed the need for four ground stations to support the constellation. The resulting raw score for ground station resiliency was 75%.

G. COST-EFFECTIVENESS

System cost and effectiveness information were entered into the cost effectiveness model to compare GFO-2 and the Nano-satellite Altimeter. A basic cost model for GFO-2 was developed and described in section D. The SPAWAR nano-satellite cost model described in section III.C was modified to estimate the cost of the Nano-satellite Altimeter. The importance and variation of measure of performance were entered in a swing weight matrix. The system performance results from STK, shown in Table 5, were entered in the model. Finally, a graph of effectiveness against the cost was created as shown in Figure 25.

GFO-2 achieved an effectiveness of 73% with an estimated cost of $265,689,164. The four Nano-satellite Altimeter system achieved an effectiveness of 26% at a cost of $109,159,000.

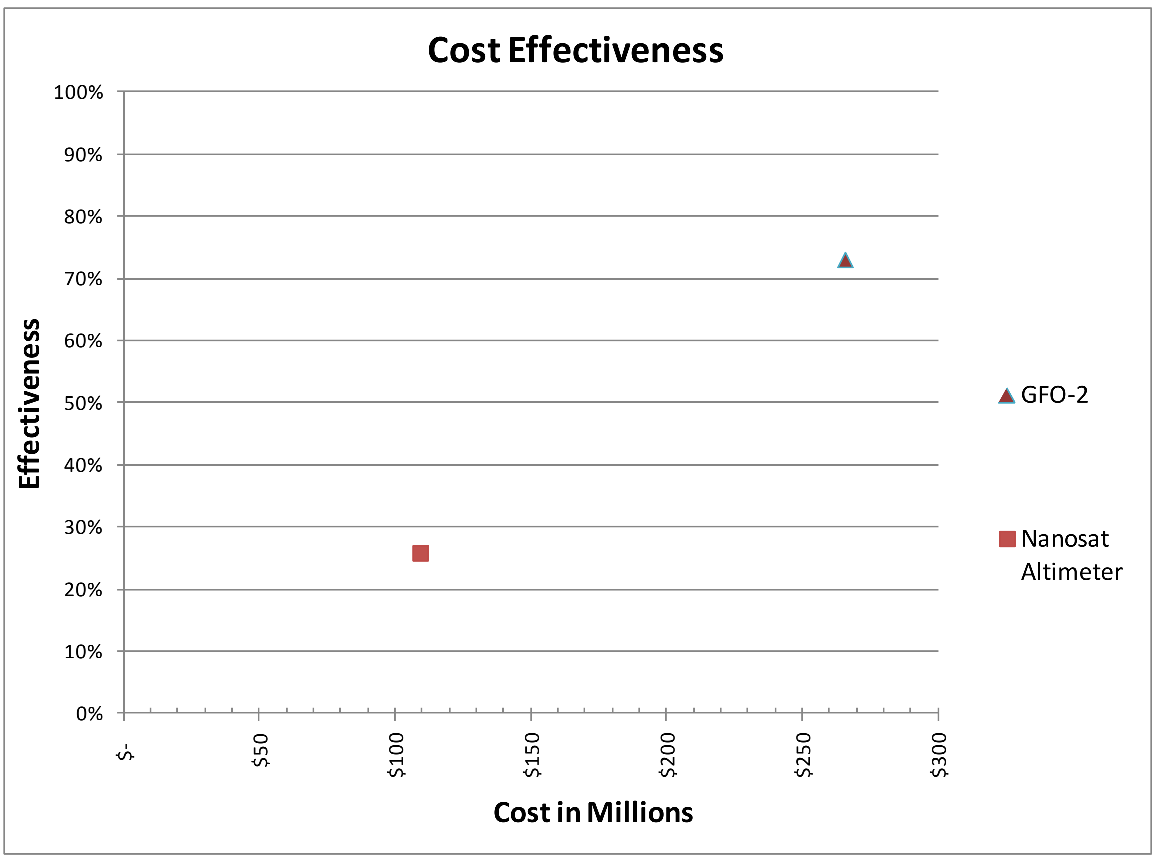

Figure 27. Environmental Monitoring Scenario Cost Effectiveness Results

VI. CONCLUSIONS

The continued miniaturization of COTS devices has enabled a surge in the number of nano-satellites designed and launched into space. As consumer electronics continue to pack more capability into consumer devices, the capability of nano-satellites will continue to grow. The commercialization of nano-satellites by companies like Planet Labs will lead to significantly reduced production costs, which will lead to even larger numbers of satellites being launched. The Department of the Navy will need to adapt to this new technology.

Cost-effectiveness analysis is a proven method to evaluate the benefit of various alternatives. It was shown to be applicable to decisions between nano-satellites and traditional space systems. The method described was applied to two vastly different missions in Intelligence, Surveillance and Reconnaissance (ISR) and Environmental Monitoring. The cost-effectiveness analysis method outlined in this thesis can be used as a template for future analysis of nano-satellite systems for any type of mission. With input from appropriate stakeholders and system experts, cost-effectiveness analysis can provide a quantitative method for high impact decision making.

The cost-effectiveness analysis showed that nano-satellites provided less capability than traditional satellites, but at a significantly lower cost. Planet Labs' Flock of imaging satellites provided nearly the same effectiveness as WorldView-2 at just over half the cost. The author's proposed NanoSat Altimeter provide just over a third of the effectiveness of the GFO-2 mission, but at slightly more than a third of the cost. Both analyses required a number of assumptions, which should be validated by experts prior to making official decisions. Even if some of the assumptions are incorrect, nano-satellites demonstrated sufficient cost-effectiveness that they should be considered in more detail for potential future space missions.

A. RECOMMENDATIONS

The Department of the Navy will face a number of challenging budget decisions in the coming years. Traditional space systems have provided significant capability to the Navy, but at a significant cost. Nano-satellites may be able to provide a subset of the capability at a lower cost, providing an intermediate option instead of a binary fund-or-cancel decision. Decision makers should use the model developed in this thesis to quantify the cost-effectiveness of nano-satellites as they make major decisions. Either of the scenarios can be used as a template that can be modified for a particular mission.

Warfighter representatives should build flexibility into the requirements generation process. Nano-satellites may not be able to fully accomplish most requirements; however, they can contribute to a number of missions at low cost. Threshold performance values should be re-examined. In the author's opinion nano-satellites may be able to meet many of the requirements of the previous generation of traditional satellites; however, warfighters continually demand improved performance by setting higher threshold values. If thresholds can be lowered, the cost-effectiveness model can then be used to find the most cost-effective solution.

The naval research and development, and acquisition communities should continue to investigate the use of nano-satellites to meet future needs. The development of this thesis showed how one person could evaluate the cost-effectiveness of nano-satellites in a reasonable amount of time. The community also needs to monitor the performance of emerging academic and commercial nano-satellite capabilities for potential naval use, or for potential use against naval forces.

The operational community should consider the implications of using nano-satellites as a platform for low cost payloads in space. The Chief of Naval Operations stated the Navy should "consider shifting our focus from platforms that rely solely on stealth…" (Greenert 2012). Nano-satellites could be launched

in large numbers at relatively low cost, providing strength in numbers instead of relying on stealth. The naval forces should consider how they would command and control a large number of satellites. They should also consider how they would operate if adversaries had large numbers of satellites.

B. AREAS FOR FURTHER RESEARCH

The scenarios presented required the launch of multiple blocks of nano-satellites across more than five years. No improvement was assumed between blocks of nano-satellites. This is inconsistent with the author's experience, where consecutive generations of nano-satellites have significantly increased capability. Future research could examine the rate of nano-satellite capability increases in various mission areas over time. Such research could then be applied to this thesis, which would likely result in increased cost-effectiveness for nano-satellites.

Most nano-satellites to date have been relatively simple systems, often with only one payload. Many new missions have been discussed which require more complex payloads or even multiple payloads. This new complexity could drive costs higher, as "Sarsfield suggests that as size decreases, complexity rather than size becomes the dominant factor in cost" (Fox, Brancato and Alkire 2008). Future research could investigate the impact of complexity on cost, perhaps by expanding Bearden's complexity index concept (Bearden 2003). Bearden's work focused on small and micro-satellites because there were few nano-satellite missions at the time. A researcher could add data on nano-satellite class systems to Bearden's dataset to determine if the complexity index concept holds for nano-satellites.

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